

# *Sandia Corporation*

Bibliography

## IMPACT PHYSICS

by

Robert Graham

*SC/118 Dup.*

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DECEMBER 1958

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SCR-59  
PHYSICS AND MATHEMATICS  
(TID-4500, 14th Ed)

SANDIA CORPORATION BIBLIOGRAPHY

IMPACT PHYSICS

by

Robert Graham  
Physical Research Department  
Sandia Corporation

December 1958

## ABSTRACT

This bibliography consists of a rather complete collection of references and abstracts on the subjects of: (1) plastic wave propagation in bounded solids; (2) behavior of metals under explosive conditions; (3) dynamic photoelasticity; (4) penetration phenomena. Other topics covered in less detail are: (5) behavior of material at high strain rates; (6) lateral impact; (7) impact measurement devices.

General references at the beginning of the bibliography cite articles or books which cover the field of impact. An author index and a chronological listing of articles within a particular topic are included.

## PREFACE

The Physical Research Department at Sandia Corporation has encountered many impact problems in its past and current activities. In order to become familiar with past work in this field, a systematic search and study of the literature was undertaken. This bibliography is the result of the literature search and is being published since comparison with other bibliographies shows it to be more complete in certain areas.

The subject of wave propagation is an important consideration in most impact problems but it was decided not to search the literature for articles dealing with wave propagation, as such, since this extensive field is the subject of several recent survey articles and books.<sup>1, 2, 3, 6, 7, 8\*</sup>

The bibliography in its final form deals with wave propagation as it applies to specific areas of interest in impact problems. The references have been assembled into groups according to the main topic of the reference. The major subjects included in the bibliography are:

1. Plastic Wave Propagation in Bounded Solids
2. Behavior of Metals Under Explosive Conditions
3. Dynamic Photoelasticity and Related Topics
4. Penetration Phenomena

All of the references listed under these subjects are articles which are technically related and which normally follow the same general trend of thought in the literature. These subjects are felt to be well developed in the bibliography. That is, the references listed can be considered as representing a high percentage of the total references on this subject. To obtain this extensive coverage a search was made of the indexes of well known applied mechanics and physics publications. The articles listed in these indexes were then obtained and the references in each article were added to the bibliography. This new list of references was searched for more references, this method being continued until the list of references given by the various articles converged.

The subjects listed below are also included in this bibliography but do not necessarily represent extensive coverage of the subject:

5. Behavior of Materials at High-Strain Rates
6. Impact Measurement Devices
7. Lateral Impact-Beams and Plates
8. Miscellaneous

The general references listed at the beginning of the bibliography are a group of articles or books which cover the field of impact rather completely. No attempt has been made to duplicate the bibliographies given in these references.

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\* Superscripts refer to reference numbers in the bibliography.

To improve the usefulness of the bibliography, a complete author index has been prepared along with a chronological listing of the references within a particular subject. The chronological listing is particularly helpful in giving the proper perspective to the various references.

The abstracts included are either the author's abstracts or short reviews made by this author.

To obtain current information on activities throughout the nation, an extensive trip has been made to the various centers of activity in this field. The observations made on this trip have been very enlightening and have served to give information which would not appear in the literature for some time. A report on this trip will be published in a Sandia Corporation Technical Memorandum.

The author hopes that users of the bibliography will call attention to errors or omissions.

The author would like to express appreciation to A. F. Beck who suggested this work, and Dr. S. E. Whitcomb who made many helpful suggestions.

## TABLE OF CONTENTS

	Page
PREFACE . . . . .	3
Reference Numbering Code . . . . .	6
GENERAL REFERENCES . . . . .	7
PLASTIC WAVE PROPAGATION IN BOUNDED SOLIDS . . . . .	9
Bibliography . . . . .	10
Chronological Listing . . . . .	22
BEHAVIOR OF METALS UNDER EXPLOSIVE CONDITIONS . . . . .	23
Bibliography . . . . .	24
Chronological Listing . . . . .	41
DYNAMIC PHOTOELASTICITY AND RELATED TOPICS . . . . .	42
Bibliography . . . . .	43
Chronological Listing . . . . .	52
PENETRATION PHENOMENA . . . . .	53
Bibliography . . . . .	54
Chronological Listing . . . . .	63
BEHAVIOR OF MATERIALS AT HIGH STRAIN RATES . . . . .	64
Bibliography . . . . .	65
IMPACT MEASUREMENT DEVICES . . . . .	71
Bibliography . . . . .	72
LATERAL IMPACT-BEAMS AND PLATES. . . . .	78
Bibliography . . . . .	79
MISCELLANEOUS . . . . .	87
Bibliography . . . . .	88
AUTHOR INDEX . . . . .	98

## IMPACT PHYSICS

### Reference Numbering Code

The references listed in the bibliography were given numbers within a group according to their subject with the following code being utilized.

	<u>Code</u>	<u>Page</u>
General References	1-100	7
Plastic Wave Propagation in Bounded Solids	1000-1099	9
Behavior of Metals Under Explosive Conditions	1100-1199	24
Dynamic Photoelasticity and Related Topics	2000-2099	42
Penetration Phenomena	3000-3099	53
Behavior of Material at High-Strain Rates	1200-1299	64
Impact Measurement Devices	2100-2199	71
Lateral Impact-Beams and Plates	4000-4099	78
Miscellaneous	5000-5099	87



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ELASTIC WAVES IN LAYERED MEDIA  
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         ASTIA AD 39616.  
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- 10       Goldsmith W, University of California, Berkeley  
         BIBLIOGRAPHY ON WAVE PROPAGATION IN SOLIDS  
         Private publication. (938 references).

PLASTIC WAVE PROPAGATION IN BOUNDED SOLIDS  
(1000-1099)

Subtopics

Experimental technique; material behavior as deduced from wave propagation characteristics; and graphical wave propagation analysis.

PLASTIC WAVE PROPAGATION IN BOUNDED SOLIDS  
(1000-1099)

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THE USE OF FLAT-ENDED PROJECTILES FOR DETERMINING  
DYNAMIC YIELD STRESS  
Proceedings of the Royal Society of London  
1948, Series A, Vol. 194, p. 289.
- The deformation of a flat-ended projectile, due to being fired at high velocity against a steel plate, is used as a measure of the dynamic yield stress of the projectile. In Part I the theory of the method is presented. Results of experimental tests are shown in Part II. Satisfactory results obtained for velocity of impacts from 400 to 2500 ft/sec.
- 1002 Johnson J E, Wood D S and Clark D S  
DYNAMIC STRESS-STRAIN RELATIONS FOR ANNEALED 2S ALUMINUM UNDER COMPRESSIVE IMPACT  
Journal of Applied Mechanics, Trans. ASME  
1953, Vol. 75, pp. 523-529.
- This paper presents the results of an experimental study of the dynamic stress-strain relations for annealed 2S Aluminum. Methods of obtaining data are presented. The technique used in analyzing the data involves the use of plastic and elastic stress-wave propagation.
- Impact velocities to a maximum of about 150 fps.
- 1003 Von Karman T and Duwez P  
THE PROPAGATION OF PLASTIC DEFORMATION IN SOLIDS  
Journal of Applied Physics  
1950, Vol. 21, pp. 987-994.
- The stress wave caused by longitudinal impact on a cylindrical bar is analyzed for the case where impact velocity is large enough to produce plastic strain. The concept of a critical velocity is presented. An experimental investigation is performed which substantiates the theoretical presentation.

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STRESS-STRAIN RELATIONS UNDER TENSION IMPACT LOADING  
Proceedings ASTM  
1938, Vol. 38, Part II, p. 98.
- Force elongation curves are obtained for several materials for an impact velocity of 11 ft/sec. It is concluded that yield forces under dynamic conditions are higher than under static conditions.
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DISCUSSION OF THE FORCES ACTING IN TENSION IMPACT TESTS OF METAL  
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1948, Vol. 70, p. 243.
- A method is described for measuring the forces acting on a specimen during a tension impact test. Plastic wave propagation theory is used to interpret the results obtained. Impact velocities to a maximum of 200 ft/sec. Very good article on interpretation of force-time curves obtained from such tests.
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University of Texas, Defense Research Lab. N. 327, CF2009.
- 1007 Lee E H and Tupper S J  
ANALYSIS OF PLASTIC DEFORMATION IN A STEEL CYLINDER STRIKING A RIGID TARGET  
Journal of Applied Mechanics, Trans. ASME  
1954, Vol. 76, p 63.
- The G. I. Taylor dynamic compression test (article 1001) is used to determine the entire strain distribution for a test cylinder of nickel-chrome steel. In the interpretation of results, interest is concentrated on the plastic and elastic wave fronts which emanate from the surface of contact. The theory of the propagation of plastic waves is presented. This is a fundamental article in relation to impacts large enough to cause plastic deformation. Impact velocities to about 1500 fps.
- 1008 Lee E H and Wolf H  
PLASTIC-WAVE PROPAGATION EFFECTS IN HIGH SPEED TESTING  
Journal of Applied Mechanics, Trans. ASME  
1951, Vol. 73, p. 379.
- This article discusses how a material test carried out at high speed may be markedly influenced by plastic-wave

propagation effects. The range of speed is determined which permits satisfactory test interpretation without the need for detailed plastic-wave analysis.

Fundamental article on the interpretation of high speed material tests.

1009

Habib E T

A METHOD OF MAKING HIGH-SPEED COMPRESSION TESTS ON SMALL COPPER CYLINDERS

Journal of Applied Mechanics, Trans. ASME

1948, Vol. 70, p. 248

Discussion Journal of Applied Mechanics, 1949, Vol. 71, p. 98.

High-speed compression tests are performed on small copper cylinders by subjecting them to the impact of a piston fired from a pneumatic gun. Experimental techniques are discussed and results of the tests are shown as energy absorbed versus deformation. The complication due to plastic strain waves is mentioned.

Velocity of impact 25-200 fps.

1010

White M P and Griffis LeVan

THE PROPAGATION OF PLASTICITY IN UNIAXIAL COMPRESSION

Journal of Applied Mechanics, Trans. ASME

1948, Vol. 70, p. 256.

Discussion Journal of Applied Mechanics, 1949, Vol. 71, p. 219.

A theoretical investigation of the mechanism of uniaxial compression impact on elastic-plastic materials is described. It is concluded that four different modes of behavior can occur, depending on the impact velocity.

1011

Sternglass E J and Stuart D A

AN EXPERIMENTAL STUDY OF THE PROPAGATION OF TRANSIENT LONGITUDINAL DEFORMATIONS IN ELASTOPLASTIC MEDIA

Journal of Applied Mechanics, Trans. ASME

1953, Vol. 75, pp. 427-434.

An experimental study is presented which is concerned with confirming the theory of the propagation of plastic waves. It is concluded that the velocity of propagation of the wave front is that of the elastic wave which is not in agreement with theory as proposed by Von Karman and Taylor.

1012

Malvern L E

THE PROPAGATION OF LONGITUDINAL WAVES OF PLASTIC DEFORMATION IN A BAR OF MATERIAL EXHIBITING A STRAIN-RATE EFFECT

Journal of Applied Mechanics, Trans. ASME

1951, Vol. 73, pp. 203-208

Discussion Journal of Applied Mechanics, 1951, Vol. 73, pp. 428-429.

The theory of propagation of plastic longitudinal waves is extended to include the strain rate effect on the stress-strain curve.

See also 1052. Bibliography contains 30 references.

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ON THE IMPACT BEHAVIOR OF A MATERIAL WITH A YIELD POINT  
Journal of Applied Mechanics, Trans. ASME  
1949, Vol. 71, pp. 39-52  
Discussion Journal of Applied Mechanics, 1949, Vol. 71, pp. 318-319.

A very complete analysis is made of impact behavior of materials with a yield point. The theory of plastic wave propagation and the combination of plastic and elastic waves is presented very clearly.

- 1015 White M P and Griffis LeVan  
THE PERMANENT STRAIN IN A UNIFORM BAR DUE TO LONGITUDINAL IMPACT  
Journal of Applied Mechanics, Trans. ASME  
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A method is presented for giving the final distribution of strains in a uniform bar subjected to a plastic impact. The wave propagation theories are used in the development. The presentation is very basic from the standpoint of interpretation of impact stresses and strain in cylindrical specimens.

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HIGH VELOCITY TENSION IMPACT TESTS  
Proceedings ASTM  
1936, Vol. 36, Part II, p. 85.

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AN EXPERIMENTAL STUDY OF THE PROPAGATION OF PLASTIC DEFORMATION UNDER CONDITIONS OF LONGITUDINAL IMPACT  
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ON THE PROPAGATION OF PLASTIC DEFORMATION IN SOLIDS  
NDRC Report No. A-29  
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THE PROPAGATION OF PLASTIC WAVES IN TENSION SPECIMENS  
OF FINITE LENGTH  
NDRC Report No. A-103  
OSRD No. 946, 1942.
- 1020 Campbell J D  
AN INVESTIGATION OF THE PLASTIC BEHAVIOR OF METAL RODS  
SUBJECTED TO LONGITUDINAL IMPACT  
Journal of Mechanics and Physics of Solids  
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- A dynamic stress-strain relation is obtained for an aluminum alloy. An SR-4 type strain gage is mounted on the specimen. The specimen is in the form of a long rod. Successively larger impacts are imparted to the specimen to obtain a stress-strain curve. Impact is applied to a steel rod then transmitted into the specimen. The effect of the steel rod is to increase the applied stress and also separates the flexural and longitudinal components due to differences in velocity of propagation.
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THE PROPAGATION OF ELASTIC VISCOUS-PLASTIC WAVES  
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THE RELATIONSHIP BETWEEN STRESS AND STRAIN IN THE TENSILE  
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Proceedings of the Institution of Mechanical Engineers, London  
1941, Vol. 145, pp. 126-134.

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GRAPHICAL ANALYSIS OF IMPACT OF BARS STRESSED ABOVE THE  
ELASTIC RANGE  
Journal of the Franklin Institute  
July 1949, Vol. 248, pp. 15-48 and 113-142.

This article gives a detailed explanation of the use  
of graphical solutions to picture and solve prob-  
lems relating to the impact of bars. A bibliography  
on impact, consisting of 45 references, is given.  
Wave propagation is pictured graphically.

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LONGITUDINAL AND TORSIONAL IMPACT IN A UNIFORM BAR WITH  
A RIGID BODY AT ONE END  
Journal of Applied Mechanics, Trans. ASME  
1950, Vol. 72, pp. 209-217  
Discussion Journal of Applied Mechanics  
1950, Vol. 72, pp. 462-465.

1048 Riparbelli C  
ON THE RELATION AMONG STRESS, STRAIN, AND STRAIN RATE  
IN COPPER WIRES SUBMITTED TO LONGITUDINAL IMPACT  
Proceedings Society for Experimental Stress Analysis  
1956, Vol. XIV, No. 1, pp. 55-70.

A series of exploratory tests of tensile impact on cop-  
per wires is presented to show that the elastic compo-  
nent of a stress wave moves at a constant velocity  
regardless of the amount of plastic deformation. Method  
consists of dropping weight on copper wire. Bright tin  
spots on wire are photographed with high-speed photog-  
raphy to observe motion of the stress waves.

1049 Alter B E K and Curtis C W  
EFFECT OF STRAIN RATE ON THE PROPAGATION OF A PLASTIC  
PULSE ALONG A LEAD BAR  
Journal of Applied Physics  
1956, Vol. 27, pp. 1079-1085.

A very thorough article on the effect of strain rate on  
the velocity of propagation of a plastic wave in a bar.  
Tests were carried out to determine how pulses of  
plastic deformation disperse during propagation along  
a lead bar. The theory of rate of propagation is re-  
viewed and experimental results are presented.  
Article contains a list of 20 references.

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ON LONGITUDINAL PLANE WAVES OF ELASTIC-PLASTIC STRAIN  
IN SOLIDS  
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- 1051      Taylor G I  
THE TESTING OF MATERIALS AT HIGH RATES OF LOADING  
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1946, Vol. 26, pp. 486-519.
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PLASTIC WAVE PROPAGATION IN A BAR OF MATERIAL EXHIBIT-  
ING A STRAIN RATE EFFECT  
Quarterly of Applied Mathematics  
1951, Vol. 8, pp. 405-411.
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THE YIELD BEHAVIOR OF MILD STEEL IN DYNAMIC COMPRESSION  
Proceedings Royal Society of London  
1956, Series A, Vol. 236, pp. 24-40.
- Experiments are described in which a mild steel speci-  
men is subjected to a compressive impact load. Stress-  
time curves are obtained and analyzed. Micrographs of  
specimens after yielding are shown to show the metal-  
lurgical mechanism of yielding.
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MATERIALS AT VERY HIGH RATES OF LOADING  
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WAVE PROPAGATION IN ANELASTIC MATERIALS, DEFORMATION  
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ON THE DEPENDENCE OF THE STRAINS IN A RAPID DEFORMATION  
UNDER IMPULSIVE LOADING BEYOND THE YIELD POINT (Russian)  
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OBSTACLE (Russian)  
Prikladnaia Matematika i Mekhanika  
March/April 1949, Vol. 13, pp. 165-170.
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SECONDARY ELASTOPLASTIC WAVE (Russian)  
Prikladnaia Matematika i Mekhanika  
March/April 1954, Vol. 18, pp. 167-180.
- 1061      Campbell W R  
DETERMINATION OF DYNAMIC STRESS-STRAIN CURVES FROM  
STRAIN WAVES IN LONG BARS  
Proceedings Society for Experimental Stress Analysis  
1952, Vol. 10, No. 1, pp. 113-124.
- An exploratory experimental program is conducted to  
determine the feasibility of using a tangent modulus  
method to determine dynamic stress-strain curves.  
Analytical procedure is outlined and experimental  
results are presented. Measurements made with SR-4  
type strain gages.
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EFFECT OF STRAIN RATE UPON PLASTIC FLOW OF STEEL  
Journal of Applied Physics  
1944, Vol. 15, pp. 22-32.
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THEORETICAL AND EXPERIMENTAL STUDIES OF PLASTIC WAVE  
PROPAGATION IN LONGITUDINAL RODS SUBJECT TO IMPACT  
Johns Hopkins University, Institute for Cooperative Research  
Contract No. DA-36-034-ORD-2366, 1956.
- A new method employing diffraction gratings of very  
short length will be utilized to study propagated plastic  
wave fronts of large magnitude. Unloading waves, re-  
flected waves from fixed and free ends. Dynamic deter-  
mination of Poisson's ratio.
- 1064      Rubin R J  
PROPAGATION OF LONGITUDINAL DEFORMATION WAVES IN A  
PRESTRESSED ROD OF MATERIAL EXHIBITING A STRAIN-RATE  
EFFECT  
Journal of Applied Physics  
1954, Vol. 25, pp. 528-536.

The longitudinal propagation of stresses above the yield  
stress in a material exhibiting a strain-rate effect is  
studied analytically. Mathematical expressions are devel-  
oped which describe the wave propagation. The system  
analyzed is a semi-infinite rod subjected to end impact.

This article is referred to by many investigators and several extensive experiments are being conducted to verify this theory.

1065

Campbell J D  
THE YIELD OF MILD STEEL UNDER IMPACT LOADING  
Journal of Mechanics and Physics of Solids  
1954, Vol. 3, pp. 54-62.

In an extension of work reported in article 1020 the dynamic stress-strain curves of mild steel are obtained. The apparatus is adapted so that the steel rod which transmits the stress to the specimen is larger than the specimen. This increases the stress transmitted into the specimen. The strain gage is attached to the specimen.

1066

Campbell J D and Maiden C J  
THE EFFECT OF IMPACT LOADING ON THE STATIC YIELD STRENGTH OF A MEDIUM CARBON STEEL  
Journal of Mechanics and Physics of Solids  
1957, Vol. 6, pp. 53-61.

Although the results of this investigation are not of particular interest the experimental technique is interesting. A similar test setup is used as in articles 1020, 1065. Stress magnitude is amplified by transmitting the impact through steel rods of two cross-section changes. This amplifies the stress about two times. Strain gages are attached to the anvil bar.

1067

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A PARADOX IN THE THEORY OF IMPACT  
Journal of the Aeronautical Sciences  
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1068

Gilhamet J and Goldsmith W (Translators)  
PROPAGATION OF PLASTIC STRAIN  
Translation of five articles from Russian and French

1. On Explosions in a Compressible Plastic Medium  
Altschuler V
2. Concerning a Dynamic Problem of Thermoelasticity  
Danilovskaya I
3. Elasto-Plastic Waves of Loading  
Bakhshian R A
4. The Propagation of Cylindrical Waves of Plastic Deformation (Torsional Impact)  
Rakhmatulin Kh A

5. The Propagation of Spherical Waves in an  
Elasto-Plastic Medium  
Luntz Ya L

University of California, Institute of Engineering  
Research, July 1953.

# PLASTIC WAVE PROPAGATION

## Chronological Listing

Year	Reference number(s)						
1958							
1957	1066						
1956	1048	1049	1053	1063			
1955	1057						
1954	1007	1060	1064	1067	1065		
1953	1002	1011	1020	1043	1068		
1952	1050	1061					
1951	1008	1012	1036	1052			
1950	1003	1047					
1949	1014	1041	1046	1054	1059		
1948	1001	1005	1009	1010	1038	1039	1058
1947	1015	1017	1030				
1946	1022	1051					
1945	1028	1037					
1944	1025	1062					
1943	1023	1024	1029	1031			
1942	1018	1019	1021	1027	1033	1034	1035
1941	1044						
1940	1042						
1939							
1938	1004						
1937							
1936	1016						
1930	1040						



BEHAVIOR OF METALS UNDER EXPLOSIVE CONDITIONS  
(1100-1199)

Subtopics

Equations of states of solids; experimental techniques; free surface velocity determinations; scabbing (analysis and experimental) and fracture.

BEHAVIOR OF METALS UNDER EXPLOSIVE CONDITIONS  
(1100-1199)

Bibliography

- 1101 Rinehart J S and Pearson J  
ENGRAVEMENT OF TRANSIENT STRESS WAVE PARTICLE  
VELOCITIES  
Journal of Applied Physics  
1953, Vol. 24, pp 462-469.
- A simple and unique technique is described for determining the particle velocity of a material subjected to high-speed loading. The force is applied to a plate that has a pellet attached on the opposite side. The propagation of the wave through the plate and pellet causes the pellet to indent the surface of the plate. Average particle velocity can be determined by measuring the depth of penetration.
- 1102 Shreffler R G and Deal W E  
FREE SURFACE PROPERTIES OF EXPLOSIVE-DRIVEN METAL  
PLATES  
Journal of Applied Physics  
1953, Vol. 24, pp. 44-48.
- A photographic technique for study of metal-free surfaces under acceleration by high explosives is presented. Methods for reducing the data from the photographic record are described. Specific results using brass plates driven by explosives are cited. (Author's abstract)
- 1103 Allen W A  
FREE SURFACE MOTION INDUCED BY SHOCK WAVES IN STEEL  
Journal of Applied Physics  
1953, Vol. 24, pp. 1180-1185.
- Free surface motion is studied by photographing the motion of the image of point light sources on a highly polished steel surface. Plate is forced by the detonation of explosives. Results are analyzed.
- For details of experimental technique, see article 1051.

- 1104 Rinehart J S  
SOME QUANTITATIVE DATA BEARING ON THE SCABBING  
OF METALS UNDER EXPLOSIVE ATTACK  
Journal of Applied Physics  
1951, Vol. 22, pp. 555-560.
- The phenomenon of scabbing is stated to be dependent on the stress distribution within a wave and a critical normal stress that is a characteristic of the material. This paper presents the results of a modified Hopkinson pressure bar experiment in which results of stress versus time and critical velocity were obtained.
- 1105 Allen W A and McCrary C L  
EXPERIMENTAL TECHNIQUE USED TO MEASURE TRANSIENT WAVES THROUGH SOLIDS  
Review of Scientific Instruments  
1953, Vol. 24, pp. 165-171.
- 1106 Walsh J M and Christian R H  
EQUATION OF STATE OF METALS FROM SHOCK WAVE MEASUREMENTS  
Physical Review  
1955, Vol. 97, pp. 1544-1556.
- Pressure magnitudes of from 150 to 500 kilobars were obtained from metals with high explosives. Free surface velocities were determined by photographing the movement of shock waves in air or argon due to the pressure wave in the material. Results are analyzed and techniques are described.
- 1107 Allen W A and McCrary C L  
TRANSIENT WAVES THROUGH STEEL PRODUCED BY IMPULSIVE LOADING  
Paper presented at meeting of American Physical Society  
Berkeley, California, December 27-29, 1951  
Abstract in Physical Review, 1952, Vol. 85, p. 769.
- The transient behavior of a thick circular plate deforming under explosive attack has been investigated. An experimental technique, based upon the principle of the optical lever has been used to measure surface oscillations as small as  $10\mu$  in amplitude. Measured particle velocities determined by this method indicate the presence of elastic and plastic waves.
- 1108 Rinehart J S and Pearson J  
SOME TENSILE FRACTURES GENERATED IN METALS BY IMPULSIVE COMPRESSIONAL LOADING  
Paper presented at meeting of American Physical Society  
Berkeley, California, December 27-29, 1951  
Abstract in Physical Review, Vol. 85, p. 768.

One aspect of the part that high intensity stress waves play in the fracturing of metal cylinders subjected to internal explosive loading has been studied. It has been found that tensile type fractures will result from the interference of reflected tensile stress waves whenever the resulting tensile stress exceeds the critical normal fracture stress of the material

Stress wave velocities have been measured for low-carbon steel, brass, copper, lead and aluminum alloys from the geometry of fracture. These velocities are in reasonable agreement with accepted values for the velocities of dilatational waves in these metals.

- 1109 Rinehart J S  
SCABBING OF METALS UNDER EXPLOSIVE ATTACK, MULTIPLE SCABBING  
Journal of Applied Physics  
1952, Vol. 23, pp. 1229-1233.

The mechanism of multiple scabbing is explained in terms of stress propagation theory. Experimental results are shown which verify the theory. Particle velocities are determined by the use of pellets in a hole drilled on the back of the plate.

- 1110 Rinehart J S  
SOME EXPERIMENTAL INDICATIONS OF THE STRESSES PRODUCED IN A BODY BY AN EXPLODING CHARGE  
Journal of Applied Physics  
1951, Vol. 22, pp. 1178-1181.

The effects of detonating explosive charges on the surface of heavy steel plates is discussed. The mechanism of failure is discussed and stress distribution is determined by conducting a hardness survey after the plate is sectioned. Experimental techniques are not discussed.

- 1111 Pack D C, Evans W M and James H J  
THE PROPAGATION OF SHOCK WAVES IN STEEL AND LEAD  
Proceedings of the Physical Society, London  
1948, Vol. 60, pp. 1-8.

An experimental investigation is presented in which transit times for the passage of a shock wave through plates are measured. Wave is instigated by the detonation of explosive. Lead and steel plates are used. Time measured by making and breaking electrical contacts.

- 1112 Rinehart J S  
WORK HARDENING OF MILD STEEL BY EXPLOSIVE ATTACK  
Journal of Applied Physics  
1951, Vol. 22, pp. 1086-1087.

- 1113      Wood R W  
OPTICAL AND PHYSICAL EFFECTS OF HIGH EXPLOSIVES  
Proceedings Royal Society, London.  
1936, Series A, Vol. 157, pp. 249-261.
- The deformation of the copper cap on an explosive detonator is studied to gain information about the mechanism of detonation. A spectroscopic investigation of the exploding materials is also made.
- 1114      Broberg K B  
SHOCK WAVES IN ELASTIC AND ELASTIC-PLASTIC MEDIA  
Kungl. Fortifikations for valtningen Befästningsbyran  
Rapport 109-12, 141 pp. 1956. Library of Congress P. B. 126210.
- Report gives interesting review of experiments on the propagation of elastic, plastic and shock waves produced by impact and by the detonation of explosive charges. The theory of wave propagation is discussed and the propagation of spherically divergent stress-waves is treated in detail. Tables of numerical values of dynamic stress-strain results for metals and other solids are presented and the fractures produced by the reflection of intense stress waves at the free boundaries of a specimen, are described and discussed. The bibliography contains 71 references in the field, most of which are recent. (Abstract as given in Applied Mechanics Review).
- 1115      Broberg K B  
STUDIES ON SCABBING OF SOLIDS UNDER EXPLOSIVE ATTACK  
Journal of Applied Mechanics, Trans. ASME  
1955, Vol. 77, pp. 317-323.
- The mechanism of the scabbing phenomenon is discussed both theoretically and experimentally. Experimental method used to determine pressure-time relation on face of plate where detonation occurs, is a modified pressure bar. Plane scabbings are obtained by inserting cylinders in hole in plate.
- 1116      Kumar S and Davids N  
ELASTIC-PLASTIC ANALYSIS OF SCABBING OF MATERIALS  
Journal of the Franklin Institute  
May 1958, Vol. 265, pp. 371-383.
- The graphical method is used to analyze stress propagation. Stress states are analyzed which can cause scabbing. No experimental work is presented.

- 1117 Kumar S and Davids N  
MULTIPLE SCABBING IN MATERIALS  
Journal of the Franklin Institute  
1957, Vol. 263, p. 295.
- 1118 Goldsmith W and Allen W A  
GRAPHICAL REPRESENTATION OF THE SPHERICAL PROPAGATION  
OF EXPLOSIVE PULSES IN ELASTIC MEDIA  
Journal of the Acoustical Society of America  
1955, Vol. 27, pp. 47-55.

Analytic expressions of displacements, velocities and stresses as a function of location and time, as solved with the use of an IBM machine, are presented in pictorial form. Presentation is applicable to spherical divergent waves in homogeneous, isotropic, elastic media of infinite extent under the waves generated by an explosion on one face of the medium. Graphs permit a rapid evaluation of the nature of the disturbance.

- 1119 PLASTIC DEFORMATION AND FORMATION OF CRACKS BY DETONATING CHARGES (Swedish)  
Ingen. Vetensk. Akad. Tidsk. Tekn. Forsk.  
1955, Vol. 26, pp. 16-25.

Author discusses the plastic deformation and some of the fractures which occur when an explosive charge is detonated in intimate contact with, or a high-velocity fragment strikes a solid body. Several specific examples that have not been heretofore reported are described. Each example is accompanied by a brief description of the other investigations that are most likely to lead to an understanding of what has taken place in each case.

- 1120 Pearson J and Rinehart J S  
SURFACE MOTION ASSOCIATED WITH OBLIQUELY INCIDENT ELASTIC WAVES  
Journal of the Acoustical Society of America  
1953, Vol. 25, pp. 217-219.

Well-known laws which govern the reflection of elastic waves that strike free surfaces obliquely, are used to deduce particle motion at the free surface of a body\_\_

The data are expected to be of value in the solution of problems connected with impulsively loaded bodies such as metal-explosive systems. (Excerpt from author's summary).

- 1121 Pearson J and Rinehart J S  
COMPUTATION RELATING TO REFLECTION OF PLANE ELASTIC  
WAVES STRIKING FREE SURFACES OBLIQUELY  
13 August 1952, NOTS TM No. 931.
- 1122 Allen W  
ELASTIC DESCRIPTION OF A HIGH-AMPLITUDE SPHERICAL  
PULSE IN STEEL  
21 April 1953, NOTS TM No. 994.
- 1123 Huth J H and Cole J D  
A THEORETICAL TREATMENT OF SPALLING  
Rand R M - 1181.
- 1124 Evans W M and Taylor G I  
DEFORMATION AND FRACTURES PRODUCED BY INTENSE  
STRESS PULSES IN STEEL  
Research, 1952, Vol. 5, pp. 502-509.
- The mechanism of plastic deformation and fracture  
due to high explosives is investigated by studying  
the fractures produced. Specimens are sectioned  
and etched. Metallurgraphic photomicrographs are  
made to study the change in crystalline structure.  
Article is well illustrated with typical fractures.
- 1125 Kolsky H and Shearman A C  
INVESTIGATION OF FRACTURES PRODUCED BY TRANSIENT  
STRESS WAVES  
Research, 1949, Vol. 2, pp. 384-389.
- The mechanism of fracture due to detonation of  
explosives is studied by observing the fractures  
of bodies of various shapes. Plastic bodies are  
used. Large plates, small plates, cylinders,  
and cones are investigated. Various fractures  
are well illustrated.
- 1126 Kochler J S and Seitz F  
THE STRESS WAVES PRODUCED IN A PLATE BY A PLANE  
PRESSURE PULSE  
1944, OSRD Report No. 3230.
- 1127 Rinehart J S and Pearson J  
CONICAL SURFACES OF FRACTURE PRODUCED BY ASYMMET-  
RICAL IMPULSIVE LOADING  
Journal of Applied Physics  
1952, Vol. 23, pp. 685-687.
- The conical surface of fracture of an explosively  
loaded thick wall cylinder is analyzed from the

standpoint of stress wave propagation. It is shown that the angle of failure is a function of the velocity of propagation of the wave. Experimental results are shown which tend to verify the explanation.

- 1128      Pearson J and Rinehart J S  
            DEFORMATION AND FRACTURING OF THICK-WALLED STEEL  
            CYLINDERS UNDER EXPLOSIVE ATTACK  
            Journal of Applied Physics  
            1952, Vol. 23, pp. 434-441.
- This article discusses the deformation and fracturing  
            of thick-walled cylinders due to internal explosives.  
            The presentation is primarily focused on describing  
            the mechanism of failure that occurs under these cir-  
            cumstances. Stress wave propagation and behavior  
            of the material are not emphasized in the presentation.
- 1129      Starr L and Savitt J  
            SPALLING PRODUCED BY DETONATION OF EXPLOSIVE IN VERY  
            HEAVY WALLED METAL TUBES  
            Physical Review  
            1952, Vol. 86, pp. 600.
- 1130      Rinehart J S  
            HARDNESS PLATEAUS AND TWINNING IN EXPLOSIVELY LOADED  
            MILD STEEL  
            Journal of Applied Physics  
            1954, Vol. 25, p. 778.
- 1131      Mallory H D  
            PROPAGATION OF SHOCK WAVES IN ALUMINUM  
            Journal of Applied Physics  
            1955, Vol. 26, pp. 555-559.
- The velocity of shock waves in aluminum and the associ-  
            ated translational motions, produced by metal-metal  
            impact, have been determined by an electrical contact  
            technique. The results obtained have been used to evalu-  
            ate an equation of state for the metal. (Author's abstract)
- 1132      Rinehart J S  
            SOME OBSERVATIONS ON HIGH SPEED IMPACT  
            U. S. Naval Ordnance Test Station  
            Technical Memorandum RRB-50  
            19 October 1949.
- 1133      Rinehart J S  
            THE BEHAVIOR OF METAL UNDER HIGH AND RAPIDLY APPLIED  
            STRESSES OF SHORT DURATION  
            U. S. Naval Ordnance Report No. 1183  
            27 September 1949.



A number of interesting effects produced as the result of detonating explosive charges in intimate contact with metal plates, rods, and tubes are described. The principal observable effects are (1) fracturing of the metal caused by a tensional stress produced as the result of the reflection of a high compressional stress wave at a free boundary, (2) the fracturing of the metal caused by high stress concentration, and (3) permanent straining of the metal. (Author's abstract)

- 1134 Scardin H  
MEASUREMENTS OF SPHERICAL SHOCK WAVES  
Communications on Pure and Applied Mathematics  
1954, Vol. 7, pp. 223-243.

Although this article is primarily concerned with shock waves produced by explosives in air, it develops the pressure versus time data on explosives. Experimental data is shown which verify the experimental results. Photographs shown from multiple-spark camera, streak camera, condenser-microphone, kerr-cell photography, x-ray-photography.

- 1135 Walsh J M, Rice M H, McQueen R G and Yarger F L  
SHOCK WAVE COMPRESSIONS OF TWENTY-SEVEN METALS  
EQUATIONS OF STATE OF METALS  
Physical Review  
1957, Vol. 108, Part 1, pp. 196-216.

An explosive system is used to drive a strong shock wave into a plate of 24 ST aluminum. This shock wave propagates through the 24 ST aluminum into small test specimens which are in contact with the front surface of the plate. A photographic technique is used to measure velocities associated with the 24 ST aluminum shock wave and with the shock wave in each specimen. Resulting pressure-compression curves are given for 27 metals. \_\_\_\_\_ pressure interval 150 to 400 kilobars \_\_\_\_\_  
Very detailed information on the various metals behavior is given. (Author's abstract)

- 1136 Bancroft D, Peterson E L and Minshall S  
Journal of Applied Physics  
1956, Vol. 27, pp. 291-298.

This article investigates the propagation of compressive waves generated by high explosive in Armco iron. The pin technique is used to obtain free surface velocities. The presentation is given to investigate whether three stable shocks are propagated. Problem of wave propagation and reflection is well discussed.

- 1138      Drummond W E  
EXPLOSIVE-INDUCED SHOCK WAVES, PART II OBLIQUE SHOCK WAVES  
Journal of Applied Physics  
1958, Vol. 29, pp. 167-170.
- The explosive production of oblique shock waves in solids is analyzed in the approximation that third and higher order terms in the shock strength can be neglected, and a procedure is developed for calculating the attenuation of the shocks. Application is made to the problem of determining the equation of state of the burned explosive gas. See also 1139. (Author's abstract)
- 1139      Drummond W E  
EXPLOSIVE INDUCED SHOCK WAVES, PART I, PLANE SHOCK WAVES  
Journal of Applied Physics  
1957, Vol. 28, pp. 1437-1441.
- 1140      Deal W E  
SHOCK HUGONIOT OF AIR  
Journal of Applied Physics  
1957, Vol. 28, pp. 782-784.
- Experiments are described in which an explosive driven plate set up a strong shock in air in contact with the plate. Free surface velocity and air shock velocity are measured by means of a high-speed framing camera which views the plate in profile.
- Experimental results are shown for pressures up to 200 bars. A 24 St Dural plate is used.
- 1141      Allen W A and Goldsmith W  
SPALL EFFECTS PRODUCED BY A CYLINDRICAL AND A SPHERICAL CHARGE OF HIGH EXPLOSIVE  
Journal of Applied Physics  
1954, Vol. 25, pp. 813-814.
- A letter to the editor discusses the feasibility of using a spherical charge in replacement for a cylindrical charge in determining spall effects on the free surface of a plate.
- 1142      Becker H  
ON SHOCK PROPAGATION IN BRASS  
Journal of Applied Physics  
1954, Vol. 25, pp. 1066-1067.
- 1143      Savitt J, Stresau R H and Starr L E  
COMPRESSION WAVE VELOCITY EXPERIMENTS WITH COPPER  
Journal of Applied Physics  
1954, Vol. 25, pp. 1307-1310.

The velocity of compression waves in copper is investigated by detonation of explosives inside cylinders. The angle of failure of the end of the cylinder is taken as proportional to the wave velocity. Theory is explained and results are compared to article 1127.

- 1144 Mallory H D  
ON THE EXISTENCE OF A BINARY REACTION ZONE AT A  
METAL-EXPLOSIVE BOUNDARY DURING DETONATION  
U. S. Naval Ordnance Laboratory 1954  
Library of Congress P.B. 122054.

This report is a summary of recent progress made in the interpretation of pin-point data. The pin technique has been used to measure the free surface velocity of aluminum targets struck by a plane detonation wave from crystalline TNT at a loading density of 0.624 g/cc. (Author's abstract)

- 1145 Rinehart J S  
DEFORMATION OF AN EXPLOSIVELY LOADED ALUMINUM SINGLE CRYSTAL  
Journal of Applied Physics  
1955, Vol. 26, pp. 1315-1318.

A hollow cylindrical single crystal of pure aluminum was deformed by detonating an explosive charge that had been placed axially within the crystal. The approximate strain rate achieved was  $10^5 \text{ sec}^{-1}$ . The object of the test was to relate the pattern of deformation to the stresses set up by the explosive and the crystallographic axes of the crystal. The reaction of the cylinder was markedly different from the reaction which would be exhibited by a similarly shaped cylinder of polycrystalline material. The deformation was non-uniform with both the fracturing and the plastic flow exhibiting a twofold symmetry that could be unambiguously related to the orientation of stress with respect to the crystallographic axes and their associated slip systems. (Author's abstract)

- 1146 Goranson R W, Bancroft D, Burton B L, Blechar T, Houston E E, Gittings E F, and Landeen S A  
DYNAMIC DETERMINATION OF THE COMPRESSIBILITY OF METALS  
Journal of Applied Physics  
1955, Vol. 26, pp. 1472-1479.

Equation of state data for Duralumin in the pressure range from 0.1 to 0.3 megabar have been determined dynamically by measuring shock and free surface velocity electrically in a plate of 24 ST Duralumin that has been stressed by a high explosive detonation. A theory is presented which allows comparison with data obtained by other experimenters, and which yields the relationship

between pressure and compression either at constant entropy or constant temperature. The empirical form chosen for the equation of state ( $p = a\mu + \beta\mu^2$ ) expresses the pressure as a quadratic function of the compression. Experimental techniques are described in detail. Five points are given for the equation of state of Duralumin in the pressure range from approximately 0.15 megabar to 0.33 megabars. Some data are also presented for cadmium and steel. (Authors' abstract)

- 1147 Pearson J and Rinehart J S  
APPLICATION OF THE ENGRAVEMENT METHOD TO THE STUDY  
OF PARTICLE VELOCITY DISTRIBUTION IN EXPLOSIVELY LOADED  
CYLINDERS  
Journal of Applied Physics  
1955, Vol 26, pp. 1431-1435.

Application of the engraving method to the study of particle velocity distribution in the wall of a thick-walled metal cylinder internally loaded with an explosive charge is described. Tests were conducted with this method on modified cylinders of annealed low-carbon steel and of brass. Even though each of the modified cylinders broke into a number of fragments, the engravements were well enough preserved to furnish considerable data. Many measurements were obtained from each cylinder by using a large number of pellets of several thicknesses. Particle velocity data were obtained to within 7/16 inch from the metal explosive interface. Temporal particle velocity distribution curves are presented for each of the cylinders. (Author's abstract)

- 1148 Minshall S  
PROPERTIES OF ELASTIC AND PLASTIC WAVES DETERMINED BY  
PIN CONTACTORS AND CRYSTALS  
Journal of Applied Physics  
1955, Vol. 26, pp. 463-469.

Experimental techniques are described by which one can observe the separation of a shock wave in a metal into an elastic wave and a slower plastic wave. The plastic-wave velocity was about 15 percent less in steel and 10 percent less in tungsten than the elastic-wave velocity, at pressures imparted by Composition B explosive. Elastic-wave velocities were the same, within experimental error, as the measured sound velocities. The pressure in the elastic wave in SAE 1020 steel, deduced from the material and wave velocities, is independent of the plastic-wave pressure within experimental accuracy, and is about 12 kilobars. SAE 1040 steel, however, does not exhibit a single characteristic elastic-wave pressure. The pressure initially is about 6 kilobars and increases to about 12 kilobars before the arrival of the plastic wave. (Author's abstract)

- 1149 Allen W A, Mapes J M and Mayfield E B  
SHOCK WAVES IN AIR PRODUCED BY ELASTIC AND PLASTIC WAVES IN A PLATE  
Journal of Applied Physics  
1955, Vol. 26, pp. 125-126.
- Letter to the editor describing shock waves in air produced by free surface velocity of plate. Shadow graphs are shown of these waves. Two shock waves shown for brass but only one wave for copper. Steel and lead also reported. No numerical results presented.
- 1150 Savitt J  
A NOTE ON SHOCK PROPAGATION IN BRASS  
Journal of Applied Physics  
1953, Vol. 24, p. 1335.
- A theoretical description is given on the propagation of longitudinal waves through a body of large lateral extent. (Plates) Combination of elastic and plastic stresses is investigated.
- 1151 Murgai M P  
APPLICATION OF THE HERTZ THEORY OF IMPACT TO EXPLOSION PHENOMENON  
Journal of Chemical Physics  
1954, Vol. 22.2, pp. 1687-1689.
- 1152 Singh Sampooran  
SPATIAL DISTRIBUTION OF FRAGMENTS OF EXPLOSIVELY LOADED THIN-WALLED STEEL CYLINDERS  
Proceedings Physical Society  
1956, Vol. 69-B, pp. 1089-1094.
- 1153 Allen W A and Goldsmith W  
ELASTIC DESCRIPTION OF A HIGH-AMPLITUDE SPHERICAL PULSE IN STEEL  
Journal of Applied Physics  
1955, Vol. 26, pp. 69-74.
- Extensive calculations have been performed with an electronic calculator to evaluate a problem in elasticity that simulates the effect of a cylindrical charge of high explosive detonated in intimate contact with a steel plate. The general method of calculation has been described in detail. Although elastic theory has been extrapolated into a regime where it is known not to apply, insight of a valuable general nature has been obtained on the nature of the negative component of the pulse. (Author's abstract)

1155

Kumar S and Davids N

## BASIC THEORY OF SCABBING-ELASTO-PLASTIC WAVE PROPAGATION

Interim Technical Report No. 10, Pennsylvania State University.

Semi-graphical approaches to the propagation of stress pulses in bars created by impacts is presented. This report consists of two main parts, viz., "Stress Jump Approach" and the "Strain Contour Approach." In the first part, after a brief discussion and development of the theory of plastic wave propagation, solutions of a number of problems with various boundary conditions for rectangular and triangular pulses of both long and short duration, are presented. An idealized stress-strain diagram for 14 ST-4 Aluminum alloy obtained in our laboratory has been used for most of the above cases. In the second part, first the theory of contour propagation in the X-T plane is developed and a set of rules that govern their geometrical patterns are presented. Then solutions are provided for most cases of reflections and interactions of the strain and velocity contours that are considered necessary for solving any given problem.  
(Authors' abstract)

1156

Dewey J, Breidenbach H I and Gehring J W

## SOME OBSERVATIONS OF ELASTIC PROPERTIES OF SOLIDS UNDER EXPLOSIVE LOADING

Ballistic Research Laboratories, Report No. 931.

The strains and shock fronts in a magnesium alloy subjected to a contact detonation have been determined from flash radiographs. From these the stresses and stress-strain ratios for the compressional and shearing strains at the shock fronts have been computed, using finite strain theory. The compressional stress-strain ratio exceeds the infinitesimal and increases rapidly with strain. The shearing stress-strain ratio is considerably lower than the infinitesimal and about that predicted from Murnaghan's second order theory,  $\mu - p$ . Much less complete observations on plate glass and Catalin 61-893 are reported and reduced. Observations on heavier materials give subsonic shock velocities under very high stresses. In all materials except glass the compression front is markedly curved, indicating a rapid decay of shock strength. (Authors' abstract)

1157

Kumar S and Davids N

## MULTIPLE SCABBING IN MATERIALS

Interim Technical Report No. 4, OOR Project TB2 -0001 (1253), Pennsylvania State University.

This report discusses first, scabbing and multiple scabbing from a phenomenological point of view, then past experiments on scabbing with critical comments. It then suggests new types of experiments and the use of an

inverse approach which could yield information on pulse shapes and some of the dynamic properties of the material. The relationships among these quantities have been determined graphically. (Authors' abstract)

1158

Davids N and Kumar S  
THE BASIC THEORY OF SCABBING IN MATERIALS WITH TWO SOLIDS IN CONTACT, PART I, ELASTIC THEORY  
Interim Technical Report No. 1, OOR Project TB2-0001 (1253), Pennsylvania State University.

Basic relationships for scab formation in a solid are developed from the point of view of elastic materials. Relationships giving the thickness of scabs are obtained for semi-infinite plates and thin rods on the basis of normally-incident pressure pulses of arbitrary form. The effect of a backing medium has been expressed in terms of impedance matching relations between the two media, and these used to determine quantitatively the reduction in stress. Criteria for required thicknesses are developed on the basis of momentum considerations. A preliminary treatment is included for spherically-diverging waves arising from a point explosion in a semi-infinite medium. Some available data are made use of in a discussion for the purpose of evaluating time constants of typical pressure pulses used in the report. (Authors' abstract)

1159

Davids N  
STRESS WAVES OF PENETRATION IN PLATES  
Interim Technical Report No. 12, OOR Project No. TB2-0001 (1253) Pennsylvania State University.

Scabbing effects in plates may be analyzed theoretically by assuming elastic stress-waves excited periodically at a point-source on its boundary. The usual classical results are inaccurate since, first, the damaging wave is the one penetrating through the plate rather than propagating along it, and second, the dimensions of the plate in practical applications are just of the order of a wavelength. A more precise boundary-value problem is worked out and resulting axial stress-wave distributions for aluminum plates are given. (Author's abstract)

1160

Kumar S  
SCABBING IN BARS AND PLATES - FURTHER STUDIES  
Interim Technical Report No. 13, OOR Project TB2-0001(1253) Pennsylvania State University.

Scabbing, a fracture phenomenon in materials, due to stress reversal of strong dynamic loads, is first discussed here from a phenomenological point of view. Then an elastic analysis for determining scab lengths both in bars and plates under plane stress and plane strain is presented. As a further refinement, after explaining briefly and applying the basic theory of

elastoplastic wave propagation in solids, a study is made of scabbing possibilities in bars by semi-graphical methods, and also the basis for the elastoplastic analysis of scabbing in plates. Implications of both the elastic and elastoplastic analyses are compared. Idealized stress-strain relations for 14ST-4 Aluminum, obtained in our laboratory, have been used. (Author's abstract)

1161

Duvall G E  
PRESSURE-VOLUME RELATIONS IN SOLIDS  
American Journal of Physics  
1958, Vol. 26, pp. 235-238.

An equation of state of the form  $P(V) = f(V) + Tg(V)$ , which is useful for condensed matter, is proposed for the illustration of thermodynamic principles. Pressure-volume relations for adiabatic and shock compressions are derived with the assumption that specific heat at constant volume is independent of temperature. These derived relations are illustrated for a "Murnaghan" equation of state, and constants of this equation for several metals are tabulated. (Author's abstract)

1162

Duvall G E and Zwolinski B J  
ENTROPIC EQUATIONS OF STATE AND THEIR APPLICATION TO SHOCK WAVE PHENOMENON IN SOLIDS  
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OOR Technical Memorandum 58-1, May 1958  
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HUGONIOT EQUATION OF STATE OF ALUMINUM AND STEEL FROM OBLIQUE SHOCK MEASUREMENT  
Stanford Research Institute, Poulter Laboratories, Lab. Technical Report 018-57, December 1957.



A new method for determining the Hugoniot equation of state of solids has been developed. This method uses an oblique shock in a wedge-shaped specimen, cut so that the oblique shock is incident at an angle close to normal over the wedge face. The oblique shock is produced by a slab of explosive, lying on top of the wedge and line-initiated, providing essentially a two-dimensional shock. Simultaneous measurement of shock and free-surface velocities down the wedge face provides the data for calculation of the Hugoniot pressure and density over a wide range on a single shot. In aluminum a pressure range exceeding 2:1 may be observed on a single shot. (Authors' Summary)

- 1167 Al'tshuler L V, Krupnikov K K, Ledenev B N, Zhuchikhin V I and Brazhnik M I  
 THE DYNAMIC COMPRESSIBILITY AND THE EQUATION OF STATE FOR IRON AT HIGH PRESSURES  
 Zhur. Eksper. i Teoret. Fiz. 34:874-85, No. 4, April 1958.

The paper describes two methods for measuring the dynamic compressibility of substances. These methods are based on determining the kinematic parameters of shock waves (propagation velocity and the mass velocity of the material behind the wave front). Using these methods in the pressure range from  $4 \times 10^5$  to  $5 \times 10^6$  atm., the adiabatic curves are obtained for the shock compressibility of iron specimens with various initial densities. The resulting experimental data is used to derive the compressibility curve at absolute zero. The curve is extrapolated to pressures for which the statistical models for an atom are valid. (Authors' abstract) (Abstract in Physics Express, July 1958).

- 1168 Al'tshuler L V, Krupnikov K K and Brazhnik M I  
 THE DYNAMIC COMPRESSIBILITY OF METALS AT PRESSURES FROM FOUR HUNDRED THOUSAND TO FOUR MILLION ATMOSPHERES  
 Zhur. Eksper. i Teoret. Fiz. 34:886-93, No. 4, April 1958.

The paper presents a method for determining pressures and densities under conditions of shock compression. The method is based on measuring the propagation velocities for high-power shock waves. The method was used to measure the dynamic compressibility of copper, zinc, silver, cadmium, tin, gold, lead and bismuth in the pressure range  $4 \times 10^5$  to  $4 \times 10^6$  atm. The highest degrees of compression (2.26 and 2.28 times) were observed in zinc and bismuth (i. e., for elements with large atomic volumes). The highest absolute density ( $32.7 \text{ g/cm}^3$ ) was registered for gold. (Abstract in Physics Express, July 1958).

Allen W A, Mapes J M and Mayfield E B  
SHOCK WAVES IN AIR PRODUCED BY WAVES IN A PLATE  
Journal of Applied Physics  
1955, Vol. 26, pp. 1173-1175.

A shadowgraphic technique has been used to measure surface motion of a series of steel plates while they deform under impact caused by 1/2-in. diameter steel cylinders fired into their back surfaces at about 2800 ft/sec. The strength of the air shock produced when an initial longitudinal wave in a plate strikes the free surface of the plate has been inferred from the measured shock wave velocity in the air. The shock strength has been related to particle velocity of the surface of the plate. The results are compared to previous work involving contact explosions of small charges on plates. (Authors' abstract)

# BEHAVIOR OF METALS UNDER EXPLOSIVE CONDITIONS

## Chronological Listing

Year	Reference number(s)								
1958	1116	1138	1139	1161	1167	1168	1163	1165	
1957	1117	1135	5	1140	1166				
1956	1114	1136	1152						
1955	1106	1115	1118	1119	1131	1145	1146	1147	1148
	1149	1153	1169	1162					
1954	1130	1134	1141	1142	1143	1144	1151		
1953	1101	1102	1103	1105	1120	1122	1150		
1952	1109	1121	1124	1127	1128	1129			
1951	1104	1107	1108	1110	1112				
1950									
1949	1125	1132	1133						
1948	1111								
1947									
1946									
1945									
1944	1126								
1943									
1942									
1941									
1936	1113								

DYNAMIC PHOTOELASTICITY AND RELATED TOPICS  
(2000-2099)

DYNAMIC PHOTOELASTICITY AND RELATED TOPICS  
(2000-2099)

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KINEMATOGRAPHY IN PHOTOELASTICITY  
Transactions American Society of Mechanical Engineers  
1932, Vol. 54, p. APM 54-9.
- Moving pictures are presented showing stress fluctuations in a beam due to impact of a falling weight. Camera Speed limited to 64 frames/sec.
- 2002 Foeppl L  
SLOW MOTION PICTURES OF IMPACT TESTS BY MEANS OF PHOTOELASTICITY  
Journal of Applied Mechanics  
Transactions American Society of Mechanical Engineers  
1949, Vol. 71, p. 173.
- Moving pictures are presented showing the stress fluctuation in beams due to the impact of a hammer. Both elastic and plastic conditions are shown. Camera speed maximum of 3020 frames/sec.
- 2003 Perkins H C  
MOVIES OF STRESS WAVES IN PHOTOELASTIC RUBBER  
Journal of Applied Mechanics, Trans. ASME  
1953, Vol. 75, p. 140.
- Moving pictures are presented which show stress waves propagating in photoelastic rubber specimens. Camera speed maximum of 5000 frames/sec.
- 2004 Frocht M M and Flynn P D  
STUDIES IN DYNAMIC PHOTOELASTICITY  
Journal of Applied Mechanics, Trans. ASME  
1956, Vol. 78, p. 116.
- Equipment and techniques are described for obtaining dynamic photoelastic stress patterns by means

of streak photography. Dynamic photoelastic stress patterns showing stress-wave propagation are given for a bar struck axially by a rigid mass. 1, 500, 000 equivalent exposures/sec.

- 2005      Durelli A J and Riley W E  
EXPERIMENTS FOR THE DETERMINATION OF TRANSIENT STRESS AND STRAIN DISTRIBUTION IN TWO-DIMENSIONAL PROBLEMS  
Journal of Applied Mechanics, Trans. ASME  
1957, Vol. 79, p. 69.

A photoelastic material of low modulus of elasticity is developed for use in stress-wave propagation studies. Dynamic and static photoelastic and mechanical properties are investigated and methods are described. Photographs of fringe patterns are shown for circular discs and beams subjected to impact. Camera speed 14, 000 frames/sec.

- 2006      Sutton G W  
A PHOTOELASTIC STUDY OF STRAIN WAVES CAUSED BY CAVITATION  
Journal of Applied Mechanics, Trans. ASME  
1957, Vol. 79, p. 340  
Discussion Journal of Applied Mechanics  
1958, Vol. 80, pp. 298-299.

Ultra-high-speed photoelastic techniques have been applied to a study of the transient stresses and strains in a photoelastic plastic when subject to cavitation. Cavitation bubbles have been photographed collapsing on the surface of a photoelastic specimen and the resulting strain wave has been photographed. The static and dynamic properties of CR-39 are determined. Camera speed 1, 000, 000 frames/sec.

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A PHOTOELASTIC STUDY OF MAXIMUM TENSILE STRESSES IN SIMPLY SUPPORTED SHORT BEAMS UNDER CENTRAL TRANSVERSE IMPACT  
Journal of Applied Mechanics, Trans. ASME  
1957, Vol. 79, p. 509  
Discussion Journal of Applied Mechanics  
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Photoelastic streak photographs were taken for beams subjected to the impact of a heavy mass. This article is primarily concerned with the interpretation of results of this study. Experimental techniques are not fully discussed.

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DYNAMIC PHOTOELASTICITY BY MEANS OF STREAK PHOTOGRAPHY  
Proceedings Society for Experimental Stress Analysis  
1957, Vol. 14, No. 2, p. 81.
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Ninth Semi-Annual Eastern Photoelasticity Conference, 13 May 1939, p. 1-11, published by the College of Engineering, Cornell University.
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- 2012 Tuzi Z  
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Scientific Papers of the Institution of Physical and Chemical Research  
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A PHOTOELASTIC STUDY OF DYNAMIC STRESSES IN STRUCTURES  
Technical Report to the U. S. Navy Bureau of Docks and Yards, U. S. Naval Civil Engineering Research and Evaluation Laboratory, Structures Research Department Port Hueneme, California, Contract No. -28149, Project Order 10703  
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PHOTOELASTIC STUDY OF STRESSES DUE TO IMPACT  
Scientific Papers of the Institution of Physical and Chemical Research  
April 1935, Vol. 26, No. 566, pp. 277-309; also Philosophical Magazine, 1936, Series 7, Vol. 21, pp. 448-473.

- 2015 Feder J C, Gibbons R A, Gilbert J T and Offenbacker E L  
THE STUDY OF THE PROPAGATION OF STRESS WAVES BY PHOTO-  
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Proceedings of The Society for Experimental Stress Analysis  
1956, Vol. XIV, No. 1, pp. 109-122.

The propagation of stress waves in CR-39 plastic is shown. Propagation is instigated by the impact of rod and by the explosion of blasting caps in contact with the specimen. Maximum photo speed was 1.25 microsec between frames. Results are analyzed in terms of wave propagation theory.

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Technical Report No. 3 to the Office of Ordnance Research, U. S.  
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STATIC AND DYNAMIC CALIBRATION OF A PHOTOELASTIC  
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STATIC AND DYNAMIC CALIBRATION OF A PHOTOELASTIC  
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1956, Vol. XIV No. 1, pp. 195-204.

A thorough investigation of the properties of CR-39 is conducted. Dynamic properties are determined by passing a stress wave through the material and using a photocell to record lightness and darkness (i. e. passage of different fringes). Techniques are fully discussed and results are analyzed.

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REFLECTION OF ELASTIC WAVES FROM A FREE BOUNDARY  
Philosophical Magazine,  
May 1955, Vol. 46 Part 1, pp. 527-541.



The photoelastic technique is used in studying the problem of reflection of stress waves at a free boundary. Photographs shown are very clear and show the reflection very descriptively. Multiple spark camera was used which could take successive pictures at times ranging from 5 microsec to 50 microsec. Very clear photographs.

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PHOTOELASTIC SHOCK INVESTIGATIONS IN THIN GLASS BARS  
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OPTICAL POLARIZATION EXPERIMENTS ON THE ELASTIC IMPACT  
THEORY OF ST. VENANT AND FLAMANT  
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A METHOD OF ASSESSING TRANSIENT STRESSES IN PHOTOELASTIC  
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Review of Scientific Instruments  
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indication that photoelasticity can be used to study  
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A PHOTOELASTIC STUDY IN VIBRATION  
Journal of Applied Physics  
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A photoelastic study of steady state vibration of a  
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 PHOTOELASTIC STRESS ANALYSIS OF A SHOCK LOADED STRUCTURE  
 Paper presented at Meeting of the Division of Fluid Dynamics,  
 American Physical Society, Ithaca, New York, 11-12 September 1951  
 Abstract in Physical Review, 1951, Vol. 84, p. 614.
- The analysis of stress propagation in solids of nonconstant section has occasioned the development of this technique, of which some of the first results are presented. High velocity moving pictures (4000 frames per second) were taken in the polariscope of specimens made out of gelatin. The specimens were struck by a hammer at various velocities between zero and 30 ft/sec \_\_\_\_\_. Moving pictures of isochromatic patterns are presented with emphasis on the boundary effects in plates of various shapes. \_\_\_\_\_.
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 PHOTOELASTIC STRESS ANALYSIS OF A SHOCK LOADED STRUCTURE  
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 Also Princeton University Department of Physics Technical Report II-9 Contract NRO61-020, N6ORi-105.
- To study the form and intensity of the stress distributions set up inside an object subjected to a shock wave, a solid model of photoelastic Bakelite was mounted in the shock tube and the stress progressions in it analyzed by means of a conventional circular polariscope. \_\_\_\_\_ (p - q) patterns were taken at 10 - 20 microsec intervals starting at the time of impact. \_\_\_\_\_.
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GLASS CRACKING CAUSED BY HIGH EXPLOSIVES  
Journal of Applied Physics  
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High-speed photographs have been obtained of the fracture of glass produced by the detonation of a high explosive charge. Using photoelastic methods, the shock waves set up in the glass can also be photographed.  
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DYNAMIC STRESS DISTRIBUTION SURROUNDING A RUNNING  
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A STUDY IN PHOTOPLASTICITY  
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Washington, May 1953.

2039 Nisida M, Hondo M and Hasunuma T  
STUDIES OF PLASTIC DEFORMATION BY THE PHOTOPLASTIC  
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Proceedings Sixth Japanese National Congress of Applied Mechanics,  
University of Kyoto, Japan, October 1956, pp. 137-140.

A proposal is made to use celluloid to represent an elastoplastic material such as a non-strain-hardening metal, and to determine stress and strain patterns in the plastic range by photoelastic techniques. The few simple examples tested indicate that not only can the plastic stress and strain distribution be determined but also the residual stress pattern after unloading can

be found. Although the time for a complete test is relatively long, the method shows considerable promise for at least qualitative studies of elasto-plastic materials in the plastic range.

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British Journal of Applied Physics  
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- A fundamental procedure for photoplastic investigations is proposed. This consists of taking two fringe photographs of the same model, one under load, the second immediately after removal of load. The difference between fringe counts at corresponding points gives the stress difference which in elastic problems is derived from a single photograph. (From authors' summary)
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Hydrodynamics Laboratory, California Institute of Technology  
Report No. 21-20, July 1955.
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REVERSIBLE PHOTOELECTRIC FRINGE COUNTING  
Review of Scientific Instruments  
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Simple modifications of a Fizeau interferometer are shown which give a sense of direction to the passing fringes, enabling a suitable counting system to operate reversibly. Very fast counts can be made accurately using an electronic circuit actuated by four phototubes sighted on four points in the fringe pattern. An oscilloscope display can be used for fractional fringe interpolation. (Author's abstract)

# DYNAMIC PHOTOELASTICITY AND RELATED TOPICS

## Chronological Listing

Year	Reference number(s)							
1958	2051	2054						
1957	2005	2006	2007	2008	2034	2036	2050	
1956	2004	2015	2016	2018	2019	2039	2044	
1955	2020	2023	2024	2025	2030	2041	2048	2053
1954	2017	2033						
1953	2003	2038	2040	2045				
1952	2013	2021	2031	2032	2035	2037	2047	
1951	2011	2028	2029	2043				
1950	2049							
1949	2002	2026						
1948	2022							
1946	2009							
1941	2027	2046						
1939	2010							
1935	2014							
1932	2001							
1928	2012							

**PENETRATION PHENOMENA**  
**(3000-3099)**

Subtopics

Hypervelocity impact; ballistic penetration and cratering due to projectile impact.

PENETRATION PHENOMENA  
(3001-3099)

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A study of high speed, metal-to-metal impact in the velocity range of 1 to 5 mm/ $\mu$ sec using 1/8 inch diameter spherical pellets is described\_\_\_\_\_. Experiments relating to the mechanism of cratering and the perforation of thin targets are presented\_\_\_\_\_. (Authors' abstract)

Projectiles given high velocities by putting a hollow cone in one face of a cylindrical explosive charge.



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THE MEASUREMENT OF FORCES RESISTING ARMOR PENETRATION  
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- (Author's abstract)
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1954, Vol. 25, pp. 704-711.

A photoelectronic apparatus has been developed which makes possible the continuous simultaneous measurement of the depth of penetration, the speed, and the deceleration of a nondeforming small-caliber projectile during armor penetration. The basic operating principle of the apparatus is to have the flight path of the projectile pass perpendicularly through a thin parallel light beam of uniform intensity which activates a vacuum type phototube \_\_\_\_\_.  
(Authors' abstract)

Decelerations as high as  $10^8$  ft/sec<sup>2</sup> ±2%.

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March 1951, Series B, Vol. 64, pp. 212-218.
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PLATE CONSISTING OF SEVERAL LAYERS, STRESSED BY IMPACT  
(German)  
Zeitschrift für Angewandte Mathematik and Mechanik, Berlin  
May 1949, Vol. 29, pp. 157-159.

The author considers two cases of impact stress in a plate consisting of several layers. \_\_\_\_\_.  
The author investigates the question of whether it is of advantage to divide the plate into several layers in order to reduce the impact force, decrease the deceleration of the point of impact and thereby decrease the shear stress around the impact center \_\_\_\_\_  
(Abstract as it appears in Applied Mechanics Review).

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RESISTANCE TO THE PENETRATION OF A BULLET THROUGH AN ALUMINUM PLATE  
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THE PHOTOGRAPHY OF HIGH-SPEED METALLIC JETS  
Meteoritics  
1953, Vol. 1, No. 1, pp. 5-10.

- 3027 Rostoker N  
THE FORMATION OF CRATER'S BY HIGH SPEED PARTICLES  
Meteoritics  
1953, Vol. 1, No. 1, pp. 11-27.

This article is a study of the craters formed by high-speed particles ( $>10,000$  ft/sec). The theories of Öpik are compared to the theory that has been used for lower velocities (volume of crater proportional to kinetic energy). Experimental results are shown.

Problem is well discussed.

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AN EFFECT PRODUCED BY OBLIQUE IMPACT OF A CYLINDER ON A THIN TARGET  
Letter in Journal of Applied Physics  
1954, Vol 25, pp. 675-676.

Letter to the editor describes a phenomenon observed when a circular steel cylinder is fired at ordnance velocities at thin lead targets (0.005 - 0.010 in).

If a critical angle of incidence of the projectile on the target is exceeded the front surface of the cylinder is marked by a series of ridges. Photographs are shown of the phenomenon.

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SURFACE ENERGY, A MODE FOR ENERGY ABSORPTION DURING  
IMPACT  
American Journal of Physics  
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The role that pulverization of the target material may play in absorbing the energy of an impacting missile is discussed. The energy absorbed depends upon the area of the new surfaces formed. Correlation is made to impact of meteorites.

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SURFACE FRICTION IN BALLISTIC PENETRATION  
Journal of Applied Physics  
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The frictional adhesion between projectile and target during a ballistic penetration has been measured with a torsion-type Hopkinson bar. The apparatus allows measurement of the torsional adhesion of a spinning projectile during target penetration. By assuming the friction resisting rotation to be equal to that resisting axial penetration, the energy loss due to friction was computed. The results show that the torque time pattern during penetration of a "mechanically" clean projectile can be predicted with the assumption of a frictional energy loss just sufficient to keep the sliding surfaces at the melting temperature of the metal. Metallographic analysis of the target metal at the projectile interface gives a further indication of a molten interface. In these tests, sliding friction accounts for about 3 per cent of the striking energy of the projectile common surface contaminants, not necessarily special lubricants, reduce this loss to less than 1 per cent. (Author's abstract)

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AN APPROXIMATE THEORY OF ARMOR PENETRATION  
Journal of Applied Physics  
1955, Vol. 26, pp. 80-82.

The problem of armor penetration of thin plates is considered from a quasi-dynamical approach. Equations are derived for the energy dissipation due to plastic deformation and for heating of the projectile target interface. Both the conical and the ogival head are considered in the application of the general equations. (Author's abstract)

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PENETRATION OF FACE-HARDENED BULLET-PROOF ARMOR BY  
SOLID CALIBER .27 BULLET  
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PENETRATING VERY THIN DURALUMIN SHEETS; THE USE OF SHIELD-  
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VELOCITY LOSS OF A 1/2 INCH MODEL PROJECTILE WHEN IT PEN-  
ETRATES 1/32 INCH COLD-ROLLED SHEET STEEL  
March 1944, U. S. Naval Research Laboratory  
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EFFECTS OF TEMPERATURE ON THE RESISTANCE TO IMPACT PEN-  
ETRATION AND HARDNESS OF SOFT HOMOGENEOUS ARMOR AND  
FACE-HARDENED BULLET-PROOF STEEL AND A DESCRIPTION OF  
A NEW BASIC FEATURE OF IMPACT PENETRATION  
June 1942, U. S. Naval Research Laboratory  
Library of Congress P. B. 120678.
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WAX MODELING STUDIES OF HIGH-SPEED IMPACT  
June 1956, Utah University  
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STUDIES OF HIGH-VELOCITY IMPACT IN WAX  
Journal of Applied Physics  
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Wax targets are used to study the condition when impact velocities are greater than the sonic velocity of the target. The penetration was found to vary linearly with the cube root of the pellet velocity up to velocities in excess of twice the sonic velocity of the target material.

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ELASTIC AND PLASTIC BEHAVIOR IN SIMPLE TARGET-PROJECTILE  
SYSTEMS  
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The dynamic interaction of steel projectiles striking aluminum alloy plates at normal incidence has been investigated for geometrically simple projectiles. Observations on the penetration craters formed by flat-nose projectiles and certain idealized stress wave considerations lead to a theory of cavity formation. This can be formulated quantitatively as the relationship of the depth of penetration to (1) impact velocity, (2) certain functions of the characteristic impedances of the target and projectile materials, and (3) an empirically determined dynamic elastic limit. This theory agrees with measurements for small projectiles traveling at velocities between 300 and 850 meters/sec. Velocity ranges of dominantly elastic and dominantly plastic target behavior can be identified. (Author's abstract)

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# PENETRATION PHENOMENA

## Chronological Listing

<u>Year</u>	<u>Reference number(s)</u>					
1958	3002	3039	3044	3045	3046	3047
1957	3001	3005	3006	3007	3040	3043
1956	3003	3004	3008	3032	3038	
1955	3013	3014	3030	3031	3041	3042
1954	3016	3028				
1953	3012	3026	3027	3029		
1952	3019					
1951	3009	3021	3022	3023	3025	
1950	3010					
1949	3015	3024				
1948	3011					
1947						
1946						
1945	2017					
1944	3033	3034	3036			
1943						
1942	3037					
1941	3018					
1939	3035					
1927	3020					

BEHAVIOR OF MATERIALS AT HIGH-STRAIN RATES  
(1200-1299)

Subtopic

Time delay for yielding.

BEHAVIOR OF MATERIALS AT HIGH-STRAIN RATES  
(1200-1299)

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 ing shock table and specimen connected to table. Speci-  
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 erated. Not short time impact.
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MATERIALS AT VARIOUS RATES OF LOADING  
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1950, Vol. 50, pp. 1035-1050.
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MEASUREMENT OF THE DYNAMIC STRENGTH OF PLASTIC  
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Zeitschrift für Angewandte Physik  
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Starting from theoretical considerations, the importance  
of experimental conditions in determining the influence

of strain rate on the mechanical properties of materials is pointed out. Some interesting and hitherto unpublished experimental results, obtained by the author by means of an electromagnetic apparatus in which copper wires were loaded by a brief, strong current impulse, are briefly discussed. The effects of the propagation of plastic waves at high-test strain rates (with strain hardening) and of the length of test bar on accuracy of measurement, are considered in this paper.

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(Author's abstract)

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The stress-strain curve of a material for dynamic loads is chosen as the basic dynamic property of the material. The importance of strain-rate and other factors affecting it are discussed and some historical remarks presented. Then the present techniques of dynamic testing are discussed. Some semi-analytic approaches to estimate the theoretical relationships are given. After this some qualitative estimates of the nature of behavior of stress-strain curves are presented. In order to be able to study the general behavior of a material under dynamic loads, the necessity of experiments with controlled strain rates is pointed out and design of some experiments of this kind is given. (Authors' abstract)



IMPACT MEASUREMENT DEVICES  
(2100-2199)

IMPACT MEASUREMENT DEVICES  
(2100-2199)

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          strain in metals under central impact. Strain-time  
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The probe described is capable of accurately measuring  
the displacement of a plane reflecting surface along its

normal without making mechanical contact with it. The image of an illuminated grating of special construction is formed on the surface to be observed, and the light reflected from this surface then forms an image of equal size on a second, exactly similar, grating. The disposition of the second image relative to the second grating depends upon the position of the probe relative to the plane surface\_\_\_\_\_.

Displacements may be measured with a standard deviation of  $2.8 \times 10^{-5}$  in. Device is apparently for static deflections but appears to have promise for dynamic conditions.

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Journal de Physique et le Radium, Paris  
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This method is suitable for measuring the displacement of a polished or plated surface. A metal plate such as a razor blade is mounted parallel to and about 0.01 mm away from the surface observation of the slit at grazing incidence shows a real and a virtual (reflected) edge. Variations in the magnitude of this "semi-virtual slit" are used to modulate a beam of light falling on a photocell for recording static or dynamic displacements of the surface.  
(Author's abstract)

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based on Hertz classical equations, concerning the  
contact between elastic solid bodies. In order to  
verify their validity and utility for this purpose, ex-  
tensive static and dynamic tests were made, where  
the contact areas between spheres and plane solid  
surfaces were measured and the corresponding forces  
observed and computed. Balls were dropped on plane  
surfaces, and new methods, one of them involving the  
use of high-speed films, were used to measure the time  
of impact and the diameter of the circular contact sur-  
face \_\_\_\_\_. (Author's abstract)
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SOME RECENT DEVELOPMENTS OF THE MECHANICAL DEFLEC-  
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RESPONSE SPECTRA BY MEANS OF OSCILLOGRAPH GALVA-  
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A response spectrum (shock spectrum) is the response of a series of a single-degree-of-freedom systems of given damping to a shock or vibratory motion, as a function of the frequencies of the simple systems. An oscillographic galvanometer is a single-degree-of-freedom system having a rotational response to an exciting current. If the exciting current is made proportional to the amplitude of the motion, the response of the galvanometer to the current will be proportional to that of a single-degree-of-freedom system to the motion, provided their natural frequencies and damping properties are the same. A commercial galvanometer-type oscillograph has been obtained having twelve undamped galvanometer elements with natural frequencies in the range between 10 and 2500 cps. Damping by electrical means, has been made adjustable between about 3 and 50% of critical. Associated circuitry have been constructed so that electrical playback of recordings of shock and vibratory motions can be conveniently analyzed. Calibration techniques are described and examples are given for analysis of simple and complex shock motions. (Authors' abstract)

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LATERAL IMPACT-BEAMS AND PLATES  
(4000-4099)



LATERAL IMPACT-BEAMS AND PLATES  
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AN EXPERIMENTAL INVESTIGATION OF BEAM STRESSES PRODUCED BY OBLIQUE IMPACT OF A STEEL SPHERE  
Journal of Applied Mechanics, Trans. ASME  
1956, Vol. 78, pp. 606-611.

An experimental investigation designed to study the phenomena incident to the oblique collision of 1/2-inch-diameter steel spheres with mild-steel and annealed drill-rod beams at oblique angles of incidence has been undertaken. Initial ball velocities ranged from 30 ft/sec to 150 ft/sec, beam sizes varied from 1/4 in. x 1/4 in. to 3/4 in. x 3/4 in., angles of incidence were chosen from 85 deg to normal incidence, and simply supported, clamped, and free beams were employed. Information is reported concerning the values of maximum bending stress at various positions along the beam as function of the angle of incidence and as a function of beam size for various angles of incidence. The progressive dispersion of the initial transient has been examined in detail. The effect of end supports, effective beam length, and repetitive shots into the same hole upon stress are described.

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KINEMATIC PHENOMENA OBSERVED DURING THE OBLIQUE  
IMPACT OF A SPHERE ON A BEAM  
Journal of Applied Mechanics, Trans. ASME  
1956, Vol. 78, pp. 612-616.

Experimental data relating to the kinetics of oblique impact of a 1/2-inch-diameter steel sphere upon steel beams at initial velocities ranging from 30 to 150 fps are presented. The variation of beam deflection, contact duration, trajectory of the sphere, and contour topography with angle of incidence, beam size, and initial velocity have been determined and the velocity of propagation of several waves has been ascertained.

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PERMANENT DEFLECTION OF A PLASTIC PLATE UNDER  
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Journal of Applied Mechanics, Trans. ASME  
1955, Vol. 77, p. 375.

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PLASTIC DEFORMATION OF SEMI-INFINITE BEAMS UNDER  
TRANSVERSE IMPACT LOADING AT THE FREE END  
Journal of Applied Mechanics, Trans. ASME  
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The object of this paper is to consider the plastic deformation of the semi-infinite beams subject to dynamic transverse loading at the free end. The type of loading considered is that of a constant bending moment, together with a transverse force the magnitude of which is inversely proportional to the square root of time. Part 1 of the paper consists of a plastic-rigid analysis of the problem, based on the plastic-rigid analysis of infinite beams under transverse, constant velocity, impact loading developed by the author. Part 2 of the paper consists of an elastic-plastic solution of the problem, based on a theoretical analysis of the plastic deformation of infinite beams subject to transverse, constant-velocity impact loading developed by H. F. Bohnblust. Specific problems are considered for which the deflection solutions obtained by elastic ideally plastic and rigid ideally plastic analyses are compared. (Author's abstract)

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subjected to impulsive loading such that the initial  
velocity is a half-sine wave, is considered in this paper.  
The elastic and elastic-plastic motions are discussed  
under the assumption that plastic flow is confined to one  
cross section, and the final deformations are compared  
with those computed from an analysis which neglects all  
elastic deformations. The purpose of the work is to pro-  
vide further information which may help in estimating the  
range of validity of the latter ("rigid-plastic") type of  
analysis. (Authors' abstract)
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RESPONSE OF AN ELASTIC DISK TO IMPACT AND MOVING LOADS  
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Proceedings Society for Experimental Stress Analysis  
1957, Vol. 15, No. 1, pp. 171-178.

Experimental results are presented for the effect of axial load on the propagation of bending waves in slender beams. Theory is presented and compared to experimental results. Application of method to measurement of tensile load in wires by using results of this work.

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OBLIQUE IMPACT OF SPHERES UPON SIMPLY SUPPORTED  
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IMPACT WITH FINITE ACCELERATION TIME ON ELASTIC AND  
ELASTIC-PLASTIC BEAMS  
Journal of Applied Mechanics, Trans. ASME  
1956, Vol. 78, pp. 411-415.

The purpose of the work described in this paper was to provide information on the elastic and plastic deformation of steel beams subjected to transverse impact. The particular impact problem treated was chosen to correspond to conditions in tests in which a beam initially at rest is struck by a massive hammer, so that a specified change of velocity is imposed at a certain cross section in a small time interval. In the present analysis the initial elastic and subsequent elastic-plastic motions were obtained by methods similar to those used by Bleich and Salvadori (3). As in (3), it is assumed that plastic deformation occurs only at a single stationary plastic hinge (in this case at the struck cross section). Results obtained are compared with those of a "rigid-plastic" solution of the same problem, in which plasticity conditions are correctly taken into account but elastic vibrations are not included.

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DYNAMIC RESPONSE OF THIN BEAMS TO AIR BLAST  
Ballistic Research Laboratories, Report No. 787.

This paper presents a comparison of the theoretically predicted and observed elastic responses of thin simply supported beams and of cantilever beams to air-blast loading. The theoretical responses are predicted from the linear "small-deflection" beam theory and compared to motions observed with a high-speed motion picture camera. The agreement of observed deflections with predicted ones is adequate for the thicker beams where the deflections were small, but inadequate for the thinner beams where the deflections were large. (Authors' abstract)

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LARGE DEFLECTIONS OF NON-UNIFORM ELASTIC BEAMS  
SUBJECTED TO TRANSIENT LOADS  
Ballistic Research Laboratories, APG, Memo Report No. 1105,  
October 1957.

This report presents a method of solving the non-linear equation for large flexing motions of thin beams subjected to transient loads. The small deflection linearized equation is solved by successive approximation, and this solution is extended to large deflections by a perturbation scheme. The solution shows that the apparent dynamic load on any normal mode is not equal to the applied load. Because no experimental results on non-uniform beams are available, large deflections for a uniform cantilevered beam are predicted from the general solution and compared with experimental results. Agreement between experimental results and the general solution is better than that between experiment and the predictions from the solution of the linearized equations. (Author's abstract)

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THE DAMPING OF TRANSVERSE VIBRATIONS OF THIN BEAMS  
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Ballistic Research Laboratories, APG, BRL Report No. 1033  
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A non-linear partial differential equation describing the free transverse vibration of thin beams in air is formulated. The equation accounts for two types of force on the beam caused by its motion through the air and for the force caused by internal friction of the beam material, in addition to the usual elastic and inertia forces. An approximate solution to the equation is obtained by a perturbation method.

A series of experiments were conducted at large initial vibration amplitude to corroborate the theory, which predicts that "pressure drag" air damping is proportional to amplitude and that "viscous drag" air damping and internal damping are independent of amplitude. The dependence of pressure drag damping on air pressure is also predicted. The experimental results show reasonable agreement with the theory; however, the importance of viscous air drag damping relative to that of internal friction cannot be determined. (Authors' abstract)

4035

Allen F J

AN ELASTIC-PLASTIC THEORY OF THE RESPONSE OF CANTILEVERS TO AIR BLAST LOADING

Ballistic Research Laboratories, Memorandum Report No. 886.

An elastic-plastic theory of the response of cantilevers loaded by air blast waves is proposed and the predictions obtained from it are compared to experimental results. The theory is capable of providing estimates for the types of beams considered; it is expected to furnish more precise estimates for certain other beams of practical interest.

A method is developed by means of which a high speed digital computing machine can rapidly and accurately predict dynamic elastic strains, moments, and deflections in certain structures. (Author's abstract)

4036

Allen F J and Rally F

A PLASTIC-RIGID THEORY OF THE RESPONSE OF BEAMS TO AIR BLAST LOADING

Ballistic Research Laboratories, Memorandum Report No. 811.

This report presents a "plastic-rigid" theory of cantilever and simply-supported beams subjected to air blast loading. The equations of motion are derived and the theoretical deformations found. Theoretically predicted permanent deformations are compared to experimentally determined permanent deformations of thin rectangular cross-section metal beams subjected to air blast load. The theory predicts correctly the occurrence of localized regions of plastic deformation, but does not accurately predict the amount of this deformation. However, the results suggest a modification of the theory which is expected to be in better agreement with experiment. (Authors' abstract)

4037

Plass H J

SOME SOLUTIONS OF THE TIMOSHENKO BEAM EQUATION FOR  
SHORT PULSE-TYPE LOADING

Journal of Applied Mechanics, Trans. ASME  
1958 Vol. 80, pp. 379-385.

A collection of solutions to the Timoshenko beam equation is presented. Various types of support conditions and impact conditions are included. In every case the impact is assumed to be a pulse in the form of a half-sine wave. The results were found numerically, using the method of characteristics, except for one case, which was done in addition by the Laplace transform method, for check purposes. Agreement with experiment is good except for a pulse of duration comparable to the time required for the bending-type wave to travel a distance of one diameter. Discussion is included of the differences among the various cases studied.

(Author's abstract)

4038

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FLEXURAL WAVES IN ELASTIC BEAMS OF CIRCULAR CROSS  
SECTION

Journal of the Acoustical Society of America  
1957, Vol. 29, pp. 42-46.

The exact equations of elasticity are employed in an investigation of the flexural vibrations of a solid circular cylinder. Contrary to previous work, it is shown that the phase-velocity-wavelength relation has an infinity of branches, thus overcoming objections, on physical grounds, which have been made to the earlier work. The three lowest branches of this dispersion relation are calculated, and these are used to study the rate of energy transmission in terms of group velocity. (Author's abstract)



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Journal of Applied Physics  
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IMPULSES  
Journal of the Acoustical Society of America  
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Shock impulses have not as yet yielded to any practical method of spectral analysis that would permit convenient exact calculation of all the peak internal responses of hardware subject to such accelerations, and also permit comparison of shock severities by inspection. The shock spectrum with a few supplementary techniques, provides adequate insight into the responses of a one degree of freedom resonator. As an indication of the responses of a system with several coupled degrees of freedom, a second-order shock spectrum is defined. An oscillatory constituent of the spectrum is also defined in such a way as to be applicable to any order of spectrum. Investigation of these two concepts leads to the conclusion that if the first-order shock spectrum technique is to be used as a basis for comparison of the severity of a laboratory test shock with that of a service shock, spectra should be plotted for both positive and negative directions. Moreover, when feasible, such spectra should ordinarily be plotted as distinct curves for the intervals during and after the test shock, and the oscillatory constituent for the interval during the shock should be estimated.  
(Authors' abstract)

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ELASTIC WAVES CREATED DURING TENSILE FRACTURE  
Journal of Applied Mechanics, Trans. ASME  
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A METHOD OF STEPWISE INTEGRATION IN PROBLEMS OF IMPACT BUCKLING  
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The equations for the dynamic buckling of an axially impacted column are discussed. A method is presented for the calculation of approximate load and deflection variations in problems of high-velocity impact. The method may be extended for cases wherein the stresses exceed the elastic limit. Results of calculations are presented for two cases. In one of these, agreement with a previous exact solution is found to be good.  
(Author's abstract)

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EXTENSION OF THE HERTZ THEORY OF IMPACT TO THE VISCO-  
ELASTIC CASE  
Journal of Applied Physics  
1955, Vol. 26, pp. 1083-1088.
- The problem considered is that of two bodies coming into normal contact over smooth curved surfaces. The initial relative velocity and the total kinetic energy involved is low. Contact is, however, confined to such small volumes of the objects involved that very high concentrations of energies are obtained at those places. The rates of application of stress are correspondingly high. The Hertz solution to this type of problem provides a useful approximation in the case of elastic objects.
- In the present treatment one of the impinging bodies is of viscoelastic material. Two viscoelastic bodies may also be treated if they are of the same material. The Laplace transform method is used to obtain the viscoelastic expression for the force developed between the two surfaces. This expression is then applied to the impact case. The expression can also be applied to other truly static cases; e. g., contact between gear tooth surfaces.
- The results are of technological interest, since it is not possible to say if a plastic is suitable for a certain category of impact applications, unless the rates of straining or stressing obtained in those applications can be estimated. (Author's abstract)
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MOTION AND STRESS OF AN ELASTIC CABLE DUE TO IMPACT  
Journal of Applied Mechanics, Trans. ASME  
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Journal of Applied Mechanics, Trans. ASME  
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IN AN ELASTIC PLATE IN PLANE STRESS  
Journal of Applied Mechanics, Trans. ASME  
1956, Vol. 78, pp. 284-286.

Detailed results are found for two plane-stress problems of an elastic plate with a hole from which a symmetrical disturbance is propagated. In the first a uniform shear stress is suddenly applied and maintained at the hole. In the second a uniform (rotary) velocity is suddenly applied and maintained. The subsequent motion is entirely rotary and involves shear stress only. The problems are mathematically analogous to those of symmetrical pressure and radial velocity at the hole, already solved by Kromm, and his analysis is followed. The existence of a similar analogy in the statistical cases is well known. (Author's abstract)

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SOME SECONDARY EFFECTS RELATED TO IMPACT WAVE  
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Journal of the Acoustical Society of America  
1957, Vol. 29, pp. 837-842.
- This paper is a theoretical analysis of simple structures  
under various types of applied impact. The results are  
presented from the standpoint of a static acceleration  
which would be required to produce the same maximum  
response in an undamped single degree of freedom system.
- Reference is made to similar work by Frankland  
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- 5040 Hoff N J  
THE DYNAMICS OF THE BUCKLING OF ELASTIC COLUMNS  
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1951, Vol. 73, pp. 68-74.
- 5041 Kornhauser M  
PREDICTION AND EVALUATION OF SENSITIVITY TO TRAN-  
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Journal of Applied Mechanics, Trans. ASME  
1954, Vol. 76, pp. 371-380.
- 5042 Orowan E  
CONDITION OF HIGH-VELOCITY DUCTILE FRACTURE  
Journal of Applied Physics  
1955, Vol. 26, pp. 900-902.
- The Griffith energy criterion,  $dW = -dU$  ( $dW$  = crack propagation work,  $-dU$  = released elastic energy), cannot be applied to essentially ductile fractures. In particular, it does not represent the condition of rapid ductile fracture propelled by the elastic energy of the specimen. The condition of such fractures is  $d^2W/dx^2 = -d^2U/dx^2$ , where  $x$  is the plastic extension accompanying the propagation of the crack.  
(Author's abstract)
- 5043 Fung Y C and Barton M V  
SOME SHOCK SPECTRA CHARACTERISTICS AND USES  
Journal of Applied Mechanics, Trans. ASME  
Vol. 80, pp. 365-372.
- 5044 Flynn P D  
ELASTIC RESPONSE OF SIMPLE STRUCTURES TO PULSE  
LOADING  
Ballistic Research Laboratories, Memorandum Report No. 525.

This paper deals with the elastic response of some simple structures subjected to a pulse loading. The structures considered are the mass on a spring, the simply supported beam, the cantilever, the circular membrane, and the clamped circular plate. The loading considered is that of a triangular pulse of pressure uniformly distributed over the area of the structural normal to the direction of motion. The pressure jumps to its peak value instantaneously and falls off linearly with increase in time, reaching



the value zero at the end of the pulse. Initially the structures are at rest and have no displacement.

The case of the simply supported beam is treated in some detail in order to illustrate the method of solution. In the other cases only the conditions necessary to specify the problem and the corresponding solutions for the deflection and strain as functions of the spatial argument and time are given. A numerical example is worked out for the simply supported beam, and the curves of deflection-time and strain-time are given for both during and after the pulse. A method is developed whereby the solutions for the triangular pulse may be modified to give directly the response of the structures to a general pressure-time loading. (Author's abstract)

- 5045 Baker W E and Allen F J  
THE RESPONSE OF ELASTIC SPHERICAL SHELLS TO SPHERICALLY SYMMETRIC INTERNAL BLAST LOADING  
Ballistic Research Laboratories, APG, BRLM Report No. 1113, August 1957.

This report presents the results of an analytical study of the reaction of an idealized nuclear reactor containment shell to internal transient loading which could be caused by reactor runaway.

The containment shell is assumed to be an elastic hollow sphere, and the transient loading is assumed spherically symmetric. A general theory of the response, valid for shells of any thickness, is developed. The theory is approximated for thin shells, and compared with experiment. The experiments corroborate the theoretical predictions. (Authors' abstract)

- 5046 Cunningham D M and Goldsmith W  
SHORT-TIME IMPULSES PRODUCED BY LONGITUDINAL IMPACT  
Paper presented at Spring Meeting of the Society for Experimental Stress Analysis, held May 14-16, 1958.

A program for the precise measurement of pulses in narrow rectangular bars generated by longitudinal impact of a 1/2-inch diameter steel ball was executed. The pulses were detected by means of resistance wire strain gages of various lengths and sandwiched piezoelectric quartz crystals, and were compared to the measured change of momentum of both ball and bar. An initial impact velocity up to 190 ft/sec always yielded permanent dents in the bar at the contact point with a depth small compared to the ball radius. Rise times of the order of 10 microseconds and peak forces of about 9,500 pounds were produced. No significant difference in the pulse shapes was observed from the records of wire-resistance strain gages and crystals,

but gages are considerably more convenient to use and are more universal in application. The impulses for longitudinal and transverse impact under similar geometric conditions appear to be comparable. (Authors' abstract)

5047

Mason P

**HIGH-SPEED FRACTURE IN RUBBER**

Journal of Applied Physics

1958, Vol. 29, pp. 1146-1150.

Cinematographic observations have been made of crack propagation under well-defined boundary conditions in rubbers at speeds up to 30 m/sec. The fracture markings showed resemblances to those obtained with metals, plastics, and glass, and could be related directly to the corresponding speed of fracture-propagation. In close analogy with Schardin's observations on glass, a noncrystallizing rubber (GR-S) showed a mode of crack propagation in which the fractured surfaces were visually smooth and the speed was about one quarter of the speed of longitudinal elastic waves. A crystallizing rubber (natural rubber) did not show this mode of propagation under the present test conditions. It is suggested that the modes of solid fracture can be usefully classified in three categories: (i) slow propagation, generally with smooth surfaces, obtained by careful control of the boundary conditions; (ii) propagation at intermediate rates with rough surfaces, involving correspondingly greater energy consumption; and (iii) fast propagation with smooth surfaces, the rate of propagation being limited by the speed of elastic waves in the material in accord with Mott's theory. (Author's abstract)

## AUTHOR INDEX

NOTE: The suffix -d after the reference number signifies that this author contributed to the published discussion.

# AUTHOR INDEX

- Abramson H N ... 3, 4001, 4011-d,  
 4038  
 Allen F J ... 4034, 4035, 4036, 5045  
 Allen W A ... 1103, 1105, 1107, 1118,  
 1122, 1141, 1149, 1153, 1169, 3028  
 Alter B E K ... 1049  
 Al'tshuler L V ... 1167, 1168  
 Alverson R C ... 4025, 4029  
 Andersen J R ... 9  
 Armstrong J H ... 2122  
 Astbury N F ... 1206  
 Atkins W W ... 3041  
  
 Backman M E ... 3040  
 Baker W E ... 4034, 5045  
 Bancroft D ... 1136, 1146  
 Barnhart K E ... 4002  
 Barret P ... 2106  
 Barstow F E ... 2046  
 Barton M V ... 5043  
 Bassett W V ... 2119  
 Bayoumi S ... 2040  
 Beedle L S ... 2113  
 Becker H ... 1142, 5016, 5038  
 Bell J F ... 1036, 1063, 2103  
 Benedick W B ... 5001  
 Bessey W H ... 1028  
 Beth R A ... 3017  
 Bethe H A ... 3018  
 Betser A A ... 2007, 2016, 2018,  
 2025  
 Birkhoff G ... 3011  
 Bisplinghoff R L ... 5036  
 Blake R E ... 5013  
 Blechar T ... 1146  
 Bleich H H ... 5025  
 Bloxsom D E ... 3045, 3046  
 Bluhm J I ... 3008  
 Boehler G ... 2011, 2028  
 Bohenblust H F ... 1019, 1021, 1034,  
 4006  
 Boley B A ... 4009, 4011, 5009  
 Brazhnik M I ... 1167, 1168  
  
 Brennan J B ... 1218  
 Brennan J N ... 4, 2126, 5037  
 Broberg K W ... 1114, 1115  
 Brown A F C ... 1044  
 Burr A H ... 1047  
 Burton B L ... 1146  
 Burton P ... 3001, 3002, 3003  
  
 Calvert N G ... 1227, 5012  
 Campbell J D ... 1002-d, 1020, 1053,  
 1065, 1066  
 Campbell W R ... 1061  
 Carlson R L ... 2115  
 Carson J A ... 2109  
 Caughey T K ... 2120  
 Chao C C ... 4011  
 Charters A C ... 2109  
 Charyk J V ... 1021, 1035  
 Christian R H ... 1106  
 Christie D G ... 2020, 2032, 2047  
 Claflin W M ... 5032  
 Clark A J B ... 2019  
 Clark D S ... 1002, 1004, 1005, 1009-d,  
 1010-d, 1017, 1029, 1033, 1035, 1213,  
 1214, 1221, 4006, 1235, 1236,  
 Clay W G ... 3004, 3038, 3039  
 Cole J D ... 1123  
 Conn W M ... 5003  
 Conrad R W ... 2124, 2128, 5019  
 Conroy M F ... 4017  
 Cooper H L ... 5035  
 Cotter B A ... 4021  
 Courtney-Pratt J S ... 2050, 2104  
 Craggs J ... 3009  
 Crede C E ... 5008  
 Cunningham D M ... 4012, 4013,  
 4028, 5046  
 Curran D R ... 1166  
 Curtis C W ... 1049,  
  
 de Callatay X ... 3032  
 de Juhasz K J ... 1046  
 Dally J W ... 2117

# AUTHOR INDEX (cont)

- Dapoigny J ... 2110  
 Datwyler G ... 1004  
 Davids N ... 1116, 1117, 1155, 1157,  
 1158, 1159, 1165, 1238  
 Davidson T ... 5028  
 Davies R M ... 6, 7, 2101, 5014  
 Davis E A ... 1216  
 Deal W E ... 1102, 1140  
 Dengler M A ... 4010  
 Dewey J ... 1156  
 Dietz H ... 2024  
 Dineff J ... 2109  
 Dohrenwend C O ... 4030  
 Doran D G ... 1166  
 Donnell C H ... 1040  
 Drucker D C ... 4030  
 Drummond W E ... 1138, 1139, 1163  
 Duby J ... 1053  
 Durelli A J ... 2004-d, 2005, 2117  
 Duwez P ... 1003, 1005, 1017, 1022,  
 1029, 1033, 1035, 4006  
 Duvall G E ... 1161, 1162
- Eder F X ... 1229  
 Edgerton H E ... 2046  
 Eisner R L ... 2054  
 Elam C F ... 1217  
 Elliot K W T ... 2105  
 Ellis A T ... 2053  
 Ely R E ... 1202  
 Eringen A C ... 4008, 4015, 4022  
 Eubank R A ... 1205  
 Evans W M ... 1111, 1124, 3023  
 Ewing M ... 8
- Fanning R ... 2119  
 Feder J C ... 2015, 2118  
 Ferguson C ... 1215  
 Feshback H ... 5021  
 Findlay W N ... 2010  
 Fink K ... 1219  
 Fischer E G ... 4031  
 Fitzgibbon D P ... 1233  
 Flynn P D ... 2004, 2008, 2013,  
 2016, 2017, 5044  
 Foeppl L ... 2002  
 Foner S ... 2035, 3021  
 Forkois H M ... 5019  
 Frankl E K ... 2040  
 Frankland J M ... 5030  
 Freeman P ... 1209  
 Fried B ... 2038, 2043  
 Frocht M M ... 2001, 2004, 2005-d,  
 2007, 2008, 2013, 2016, 2025,  
 2052
- Fung Y C ... 5043  
 Fusfeld H I ... 2118
- Gehring J W ... 1156, 3012  
 Gerard G ... 2125, 5016, 5038  
 Gibbons R A ... 2015  
 Gilbert J T ... 2015  
 Gittings E F ... 1146  
 Goland M ... 4010  
 Goldsmith W ... 10, 1118, 1141,  
 1153, 2051, 4002, 4012, 4013,  
 4028, 5046  
 Goodier J N ... 2130, 5024  
 Goranson R W ... 1146  
 Greenfield M ... 1030  
 Griffis L ... 1010, 1015, 1023, 1031
- Habib E T ... 1009, 1030  
 Hansen R J ... 2123  
 Harrington J P ... 1203  
 Harris D B ... 1212  
 Harris J I ... 4033  
 Hasunuma T ... 2039  
 Hawkes G A ... 1224  
 Hawkyard J B ... 1209  
 Heine-Geldern R V ... 2035, 3021,  
 3027  
 Hendricks C D ... 3014  
 Hetenyi M ... 2037, 2048  
 Hitch H ... 2011, 2028  
 Hodge P H ... 5023  
 Hoff N J ... 5040  
 Hollaman J H ... 1062  
 Hondo M ... 2039  
 Hopkinson B ... 2101  
 Hoppman 2nd W H ... 4005, 4007, 5006  
 Houston E E ... 1146  
 Hudson D E ... 2116, 2120  
 Hudson G E ... 5031  
 Huth J H ... 1123, 3004, 3007  
 Hyers D H ... 1019, 1021
- Irwin G R ... 3035
- Jahn R G ... 2029  
 Jahsman W E ... 2130, 5024  
 Jardetzky W ... 8  
 James H J ... 1111  
 Jantzen A C ... 3036  
 Johnson J E ... 1002, 1236  
 Jones J L ... 2127
- Katz S ... 1166  
 Kieffer J ... 2110

# AUTHOR INDEX (cont)

- Kilner D D ... 2048  
 Kinser G D ... 3033, 3034, 3036,  
 3037  
 Kirby P L ... 2107  
 Kissinger C W ... 2129  
 Klinger R F ... 1228  
 Kochler J S ... 1126  
 Kolsky H ... 1, 1054, 1125, 1237,  
 2031, 2032  
 Kornhauser M ... 5041  
 Krafft J M ... 1220, 2108, 3030, 5017  
 Krupnikov K K ... 1167, 1168  
 Kulterman R W ... 5001  
 Kumar S ... 1116, 1117, 1155, 1157,  
 1158, 1160, 1164, 1165, 1238  
  
 Lamb G L ... 4024  
 Landeen S A ... 1146  
 Lankford W T ... 2115  
 Lawson A W ... 1027  
 Lebedev N F ... 1060  
 Lee E H ... 1002-d, 1007, 1008,  
 1010-d, 1012-d, 1014-d, 1024,  
 1025, 1043, 1046-d, 1057, 4004  
 Ledenev B N ... 1167  
 Lensky V S ... 1059  
 Leth C F A ... 4023  
 Lindsay J L ... 3016  
 Locklin ... 4032  
 Loginova M A ... 1058  
  
 MacCarthy J G ... 5034  
 MacDonald R J ... 2115  
 MacDougall D P ... 3011  
 MacLaren D D ... 2113  
 McCrary C L ... 1105, 1107  
 McQueen R G ... 5, 1135  
 Maiden C J ... 1066  
 Mallory H D ... 1131, 1144  
 Malvern L E ... 1002-d, 1012, 1052  
 Manjoine M J ... 1210, 1211  
 Mann H C ... 1016  
 Mapes J M ... 1149, 1169, 3028  
 Marshall D F ... 2034  
 Masket A V ... 3015, 3016, 3033  
 Mason H L ... 4003  
 Mason P ... 5047  
 Maxwell B ... 1203  
 Mayfield E B ... 1149, 1169  
 Meier J H ... 5028, 5039  
 Meyer R H ... 1230  
 Miklowitz J ... 5007  
 Miller P ... 1027  
  
 Mills ... 4032  
 Mindlin R D ... 5025, 5035  
 Minshall S ... 1136, 1148  
 Mintrop H ... 2112  
 Monch E ... 2042  
 Monica R E ... 1203  
 Moore P ... 4030  
 Mori D ... 4027  
 Morrow C T ... 5002  
 Murgai M P ... 1151  
 Murray W M ... 2027  
 Muster D F ... 1205, 2111  
 Mutschler E C ... 2035, 3021  
  
 Nadai A ... 1014-d, 1211  
 Neilson F W ... 5001  
 Nestler D E ... 9  
 Nisbet J S ... 2126, 5037  
 Nishiwaki J ... 3025  
 Nisida M ... 2014, 2039  
 Norris G W ... 2051  
  
 Offenbacker E L ... 2015  
 Ogibalov P M ... 1058  
 Orowan E ... 5042  
  
 Pack D C ... 1111, 3023  
 Pagel H J ... 4020  
 Papirno R ... 2125  
 Pardue T E ... 1208  
 Parker E R ... 1215, 1222  
 Partridge W S ... 3038, 3039  
 Pearson J ... 2, 1101, 1108, 1120,  
 1121, 1127, 1128, 1147  
 Pederson A H ... 5034  
 Perkins H C ... 2003  
 Perls T A ... 2129  
 Peterson E L ... 1136  
 Pian T H H ... 5020, 5036  
 Plass H J ... 3, 1006, 4037  
 Pope J A ... 1232  
 Post D ... 2033, 2036  
 Press F ... 8  
 Pugh E M ... 2035, 3011, 3021, 3026  
  
 Rakhmatulin K A ... 1037, 1038  
 Rally F ... 4036  
 Rice M H ... 5, 1135  
 Riley W F ... 2005  
 Rinehart J S ... 2, 1101, 1104, 1108,  
 1109, 1110, 1112, 1120, 1121,  
 1127, 1128, 1132, 1145, 1147,  
 3010, 3019, 3029, 3042

# AUTHOR INDEX (cont)

- Ringleb F O ... 5022  
 Riparbelli C ... 1007-d, 1048, 1067,  
 2011, 2028  
 Ripperger E A ... 3, 1234, 2130, 4001  
 Rostoker N ... 3027  
 Ruhl K ... 4020  
  
 Salvadori M G ... 4018  
 Savitt J ... 1129, 1143  
 Scardin H ... 1134  
 Schardin H ... 2049  
 Schmitt A F ... 5010  
 Schwieger H ... 2023, 2024  
 Scott E B ... 3020  
 Seiler J A ... 4021  
 Seitz F ... 1027, 1126  
 Senior D A ... 2009  
 Shanley F R ... 1041  
 Shapiro G S ... 1038  
 Shearman A C ... 1125  
 Shepler P H ... 5029  
 Shi Y Y ... 1237  
 Shoup N H ... 2038  
 Shreffler R G ... 1102, 5004  
 Siddall J N ... 5020  
 Singh S ... 1152  
 Smith E A ... 1222  
 Smith R C ... 1208  
 Sokolovsky V V ... 1039  
 Solodovnikov R V ... 4019  
 Sonntag G ... 3024  
 Spells R E ... 3022  
 Stanton J S ... 2026  
 Starr L ... 1129, 1143  
 Sternglass E J ... 1011  
 Streeter J R ... 3033  
 Stresau R H ... 1143  
 Stuart D A ... 1002-d, 1011  
 Stubner F W ... 5035  
 Sullivan ... 1220  
 Sutton G W ... 2006, 2030  
 Symonds P S ... 4014, 4021, 4023  
  
 Taylor G I ... 1001, 1026, 1042, 1051,  
 1124, 3011  
 Taylor I J ... 2113, 2114  
 Terrell O D ... 2116  
 Thompson J S ... 3007  
 Thompson L T E ... 3020  
 Thomson R A ... 2052  
 Thomson W T ... 3031  
 Tillett J P A ... 5026, 5027  
 Tipper ... 1220  
 Tupper S J ... 1007, 1025  
  
 Turner T H ... 1223  
 Tuzi Z ... 2001-d, 2012, 2014  
  
 Van Valkenburg M E ... 3004, 3007,  
 3013, 3014  
 Von Karman T ... 1003, 1018, 1019,  
 1022  
 Vanek J ... 5015  
 Vigness I ... 1208, 2121, 2124, 2128,  
 4026, 5019  
 Vincent N D G ... 1044  
 Vodar B ... 2110  
 Volterra E G ... 1201, 1205, 2022,  
 2111, 4001-d  
  
 Walsh J M ... 5, 1106, 1135, 5004  
 Walsch J P ... 5013  
 Wang A J ... 4016  
 Warnack F V ... 1218, 1232  
 Webster R A ... 3035  
 Weidlinger P ... 4018  
 Welch N P ... 5033  
 Wells A A ... 2009, 2036  
 Whiffin A C ... 1001  
 White M P ... 1007-d, 1010, 1014,  
 1015, 1023, 1032, 1212  
 White W C ... 3019  
 Wickersham P D ... 4010  
 Willig F J ... 5004  
 Wilson D C ... 2105  
 Wilson W G ... 3028  
 Winslow G H ... 1028  
 Wolf H ... 1008  
 Wood D S ... 1002, 1008-d, 1012-d,  
 1029, 1033, 1035, 1050, 1214,  
 1221, 1235, 1236  
 Wood R W ... 1113  
  
 Yarger F L ... 1135  
 Yorgiadis A ... 1007-d, 1046-d  
  
 Zaid M ... 3001, 3002, 3003  
 Zandman F ... 2021  
 Zener C ... 1062, 5021  
 Zhuchikhin V I ... 1167

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